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THE RELATION OF SIZE OF STIMULUS AND INTENSITY IN THE HUMAN EYE: I. INTENSITY THRESHOLDS FOR WHITE LIGHT[1]

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It has been known since the time of Förster (**7**) and Aubert (**6**) that an inverse relation exists between the size of the retinal image and the intensity of light required to evoke a threshold response. Since these early observations a great number of experiments have been concerned with the area-intensity relation and a variety of formulations has been presented. Of the laws which have been proposed, Ricco's (**28**) is the most famous. This states that the product of area and intensity is constant for threshold excitation in the fovea of the human eye. Its analogue for the peripheral retina is Piper's law (**26**) which states that the product of intensity and the square root of area is a constant. These two laws have provided a basis for a considerable controversial literature. Ricco's law has been verified for limited ranges of area by a number of investigators (*e.g.*, Kühl, **21**; Loeser, **22**; Houstoun, **19**; Löhle, **23**) and Piper's law has also received a certain amount of support (Löhle, **23**; Henius, **18**).

It has been obvious for a long time that both Ricco's law and Piper's law are approximations which hold only for a limited range of areas in the fovea and in the periphery

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(Kleitman and Piéron, **20**). Löhle's work (**23**) has been important in clarifying this point, and he has been able to show that Ricco's law holds in both the periphery and fovea if the visual angle subtended by the threshold object is less than 10 min. For peripheral excitation Piper's law holds for visual angles between the limits of 2° and 7°. Deviations from both expressions have been noted by a number of other investigators (*e.g.*, Abney, **1**; Abney and Watson, **3**; Henius, **18**; Fujita, **9**; Piéron, **25**) and it is clear that the empirical relationship obtained depends upon the range of areas examined. A further complication demonstrated by Löhle lies in the fact that with very large areas the intensity threshold remains unchanged with a change in area.

The foregoing discussion makes it clear that the area-intensity function for the human eye over a great range of areas cannot be described by any of the equations mentioned. Indeed it would be surprising if it could, for there is no rational basis for any of the equations employed. The necessity for a rational account has been recognized by Wald (**30**), who has shown, in a recent report, that data on the area effect may be described by a theory based on the statistical properties of the retinal mosaic. Wald's analysis leads to the expression $(A - n_t)^k I = C$, in which n_t represents a constant threshold number of elements and k and C are constants. When n_t is small in comparison with A and k equals unity, the expression reduces to Ricco's law. Wald has successfully fitted this theoretical equation to his own data for the periphery and to the data of Abney (**1**) and Piéron (**24**) for the fovea. As Wald points out, the theory cannot hold for very large and very small areas.

The present experiments have been planned in order to test an hypothesis which emphasizes the spatial characteristics of the visual excitatory process. The report presents new observations on the area-intensity relation for the periphery and fovea of the human eye and the results are shown to be in good agreement with the quantitative requirements of a possible physiological mechanism. Although there is available a great body of data on the problem, we

felt that it would be worth while to accumulate a new series of measurements. We have done this after an examination of the methods used by earlier experimenters. The examination has convinced us that an improvement in some of the experimental methods employed would lead to more reliable results.

A review of earlier work brings to light four major shortcomings: (1) The data are not extensive enough. In few of the early experiments was a sufficiently large range of areas employed. This shortcoming is seen in the work of Piper (**26**), Henius (**18**), and Fujita (**9**), to take but a few examples. None of these men worked with peripheral areas having diameters smaller than 1°. In other experiments where the range was large enough the measurements were not sufficiently numerous (Kleitman and Piéron, **20**). (2) Variation in the size of the retinal image was often accomplished by moving the subject away from or toward the stimulus patch (Henius, **18**; Fujita, **9**; Löhle, **23**; Houstoun, **19**). Freeman (**8**) has shown that this procedure introduces anomalous results; and it is clear that, in a well controlled experiment, the distance of the subject from the stimulus patch must remain unchanged. (3) In some experiments heterogeneous parts of the retina were stimulated (*e.g.*, Henius, **18**; Heinz and Lippay, **17**). Typically exhibiting this difficulty are those experiments in which an increase in the size of a foveal area has probably involved the bringing in of peripheral elements (Abney, **1**). (4) Fixation conditions were usually inadequate (*e.g.*, Loeser, **22**; Heinz and Lippay, **17**; Löhle, **23**; Reeves, **27**). Adequacy of fixation is an important requisite for the fovea, and it is of importance in peripheral determinations if stimulation of a homogeneous population of elements is desired.

Because of these methodological considerations we have performed our experiments with due regard for all of the difficulties enumerated. (1) In the fovea we have used an adequate number of circular areas with diameters covering a range of 1.86′ to 1°; in the periphery the range is from 1.86′ to 25° 6′. (2) In line with the observations of Freeman (**8**), we have controlled for the possibility that distance between

subject and stimulus patch might influence our results by maintaining the observing distance constant in any given series of experiments. (3) The areas were situated in the retina so that they stimulated relatively homogeneous regions. Stimulus conditions were such that in the fovea no area, except perhaps the largest, could be expected to involve an appreciable number of rods, and in the periphery the eccentricity of regard was at such an angle that even the largest areas were well beyond the limits of the fovea. (4) We feel that fixation conditions in our experiments are better than in most of the earlier work. In the peripheral determinations, fixation was maintained constant by the provision of a foveal fixation cross, and for the foveal measurements, we have devised a method which has given highly reproducible results.

Apparatus and Procedure

Observations were made in a darkroom. In one wall of the subject's darkroom is placed an opal-glass screen which can be illuminated by means of an optical system in an adjacent dark room. The extent of the illuminated areas on the opal-glass screen is regulated by apertures of various sizes which are cut in a series of cardboard screens. The cardboard screens may be slid snugly in front of the opal glass in such a way as to restrict the light to the illumination transmitted by the circular aperture. For the large areas, these apertures were cut directly in the cardboard, but for the small areas they were cut in brass strips, each strip being centered on an opening in its corresponding cardboard screen.

For the peripheral determinations the subject's fixation was controlled by means of a foveal fixation cross. Two series of determinations were made for the periphery: one with the eye of the subject at a distance of 70 cm. from the fixation cross; the other with the eye at 230 cm. At the fixation distance in either series the arms of the cross subtend a diameter of 1°, and the thickness of each arm subtends a visual angle of 15 min. The cross is cut in cardboard and is backed with several sheets of red cellophane and a sheet of opal glass, the whole serving as the front of a light-tight box containing a 6-volt flashlight bulb. This lamp is attached, through a 6-volt transformer and a series resistance, to the alternating current line. Throughout the experiments the intensity of the fixation cross remained constant at about 0.13 millilambert. The subject regarded the cross through a stereoscope hood from which the prisms had been removed at a distance of either 70 cm or 230 cm. For both series of determinations the center of the stimulus patch was at a visual angle of 31.5° to the right of the fixation cross along the horizontal axis, an angular separation which ensures that even our largest areas are well outside the limits of the fovea. The distance of the subject's eye from the stimulus patch was the same as the distance from the fixation cross. During the experiments on the periphery, determinations were made on the left eye of the subject, and the conditions of the experiment were such that the stimulus patch appeared on the temporal half of the retina, a necessary condition if complications due to the blind spot are to be avoided.

In the series on foveal thresholds a light-adapting screen was provided for the subject. This consists of a box containing 2 frosted bulbs which illuminate an opal glass plate on one face of the box. The opal glass surface (36 × 25 cm) was placed at a distance of about 4½ ft from the eyes of the subject, and presented an adapting intensity of 303 millilamberts. The lights in the box were run at 110 volts D.C.

For foveal fixation we used the following procedure: The subject, at a distance of 230 cm from the stimulus area, regarded the stimulus area as it appeared through an aperture in a dimly illuminated background screen. This screen consists of a large white cardboard, in the center of which is a circular hole having a diameter, in terms of visual angle, of 1½°. The screen is 10 cm in front of the card bearing the stimulus apertures, and the subject had to regard the threshold stimuli through the aperture in the white cardboard. Dim illumination on this white cardboard is provided by flashlight bulbs in two small boxes faced with opal glass. Since the sides of each box are directly against the cardboard, the illumination about the circular aperture takes place at a very sharp angle. The boxes containing the background lights are shielded from the eye of the subject, the shields extending to within a distance of 8.5 cm from the edge of the aperture. As the subject regarded this configuration it appeared to him as a rectangular dimly illuminated background in the center of which was a circular, black expanse. In the determination of thresholds, the stimulus area appeared directly in the center of the black circle. Care was taken to see that no light from the background illumination influenced the illumination of the stimulus patch. Under the conditions described, the background illumination was constant throughout the experiments, but varied somewhat in different regions. Measurements made by a Macbeth illuminometer at a short distance from one edge of the circular aperture indicated that the illumination was of the order of 0.02 millilambert. This method of fixation resulted in adequate and uniform determinations of foveal thresholds. There may arise the question as to whether the background illumination influenced the threshold values, but it might be expected that this would occur in a uniform manner, and we doubt seriously if there would be any effect across the dark expanse which separated the edge of the background from the largest of our foveal areas. Fixation under these conditions then simply required that the subject regard the center of the black area in the white screen and report on the appearance of the threshold light. Observations were with the left eye.

The optical system for illuminating the stimulus patches is placed in a darkroom adjacent to the one in which the observations were made. Light rays from a 200-watt, 115-volt, concentrated filament lamp (of the type used in 16 mm. moving picture projectors) pass through a glycerine-filled cooling cell, and on emerging from the cell they encounter a hand-operated shutter, which, when open, allows the passage of rays to a Wratten neutral tint wedge (range 1 to 100) and its associated balancing wedge. In front of the balancing wedge is a holder for neutral tint filters. After passing through the wedges and filters the beam diverges further and finally illuminates the milk glass screen behind the stimulus areas in the wall of the subject's darkroom. Under these conditions the stimulus illumination consists of 'white' light. Adequate light shielding is provided, and there is little possibility that stray light can produce anomalous results.

In the experimental series on the periphery the subject was allowed a half-hour's dark adaptation before any determinations were made. At the end of this interval he was told to regard the red fixation cross and to report on the appearance of light in his peripheral field of vision. The threshold was determined by the experimenter, who

opened the shutter and then slowly but steadily moved the wedge in the less dense direction until the subject reported that he saw the light. Four determinations were made in rapid succession for each stimulus area, and a single day's series included 13 areas. After each four determinations on a single stimulus patch the subject remained in the dark while the experimenter made the necessary readjustments in apparatus for the presentation of another area. Four such series were made for each of the two subjects (CHG and RHB) at each observation distance (70 cm or 230 cm), the order of determinations varying in the four series. In one series, determinations started with the smallest area and progressed to the largest; in another they progressed from the largest to the smallest. In the other two series they started with areas of medium size and progressed to the extremes by different orders.

It was considered that adaptation conditions would play an important rôle in the foveal determinations, and for this reason we adopted the following procedure for the measurements. The subject was given 15 seconds of light adaptation followed by 105 seconds of dark adaptation before determinations were made on a given stimulus patch. At the end of the dark adaptation interval the experimenter determined the foveal threshold in a manner similar to that used in the periphery. After the two minutes of combined dark-and-light-adaptation the experimenter made four determinations on a single stimulus area, a procedure that involved approximately three minutes. When this had been accomplished, the light adaptation screen was illuminated for fifteen seconds and the process was repeated for another area. Nine differently sized areas constituted a day's series for the fovea, and four complete series were obtained with each of the two subjects. The orders of presentation of stimulus cards were similar to those used in the series on the periphery. Determinations were made with the left eye.

Results

The averaged results are presented in Tables I and II and Figs. 1 and 2. Table I and Fig. 1 present the data for the fovea, and Table II and Fig. 2 the data for the periphery.

TABLE I

Foveal Determinations—Observed and Calculated Values of Log *I*
Subject at distance of 230 cm.

Radius of Stimulus (mm.)	Radius in Minutes	Log Intensity (millilamberts)	
		Observed	Calculated from Equation (5)
0.62	0.93	−1.24	−1.23
0.84	1.24	−1.45	−1.46
1.41	2.10	−1.80	−1.80
2.04	3.03	−2.04	−1.99
3.15	4.67	−2.18	−2.17
5.60	8.30	−2.33	−2.36
8.50	12.7	−2.47	−2.46
12.0	17.8	−2.53	−2.53
20.3	30.0	−2.68	−2.62

TABLE II

PERIPHERAL DETERMINATIONS
Observation distance—70 cm or 230 cm
Theoretical values not calculated for the 230 cm distance

Radius of Stimulus (mm.)	Radius in Minutes	Observation Distance		
		70 cm.		230 cm.
		Log *I* Observed (millilamberts)	Log *I* Calculated from Equation (6)	Log *I* Observed (millilamberts)
0.62	0.93			−1.86
0.84	1.24			−2.16
1.41	2.10			−2.54
0.62	3.00	−2.98	−2.13	
2.04	3.03			−2.92
0.84	4.10	−3.28	−2.78	
3.15	4.67			−3.28
1.41	6.90	−3.68	−3.51	
5.60	8.30			−3.71
2.04	10.0	−3.98	−3.96	
8.50	12.7			−3.98
3.15	15.5	−4.31	−4.38	
12.0	17.8			−4.17
5.60	27.5	−4.76	−4.79	
20.3	30.0			−4.56
8.50	42.0	−5.13	−5.03	
32.0	47.6			−4.83
12.0	59.0	−5.20	−5.18	
55.0	81.8			−5.08
20.3	100.0	−5.42	−5.37	
98.0	145.7			−5.22
32.0	160.0	−5.49	−5.50	
156.0	231.7			−5.35
55.0	272.0	−5.65	−5.61	
98.0	480.0	−5.68	−5.70	
156.0	753.0	−5.76	−5.76	

Because of later theoretical treatment the tables present the intensity threshold as a function of the radius of the stimulus area rather than of the area itself (first column). The tables (second column) also indicate the visual angle in minutes subtended by the radius. Through this measure it is possible to present data obtained with the subject at the different distances from the fixation cross in comparable units, and the log radius values of Figs. 1 and 2 are presented in these units. In Fig. 2 the data for the observation distance of 230 cm are moved downwards along the ordinate through a distance of 0.25 log unit in order to indicate their general agreement with

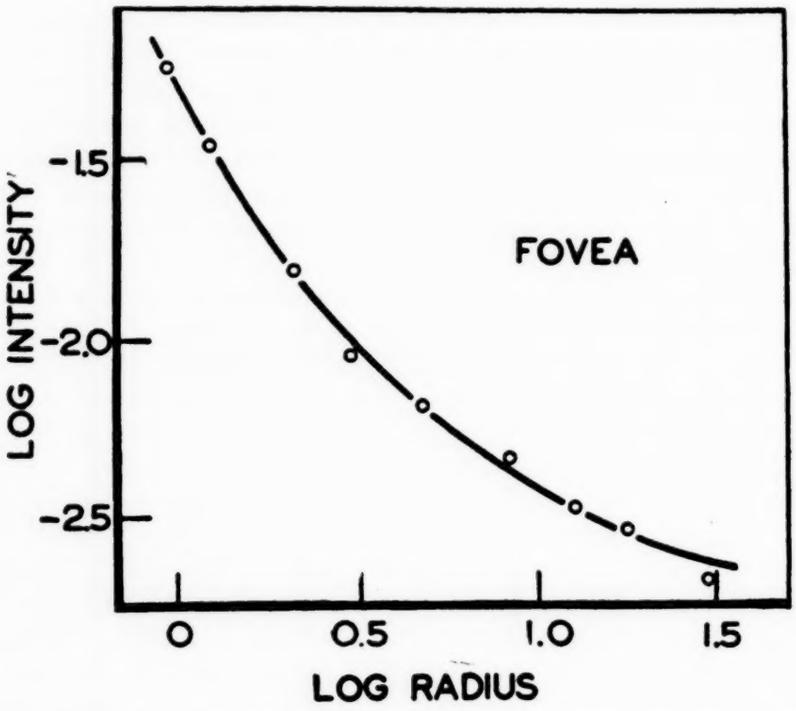

FIG. 1. The foveal intensity threshold as a function of the stimulus radius. The curve drawn through the data is computed from equation (5). Conditions of the experiment are as described in text.

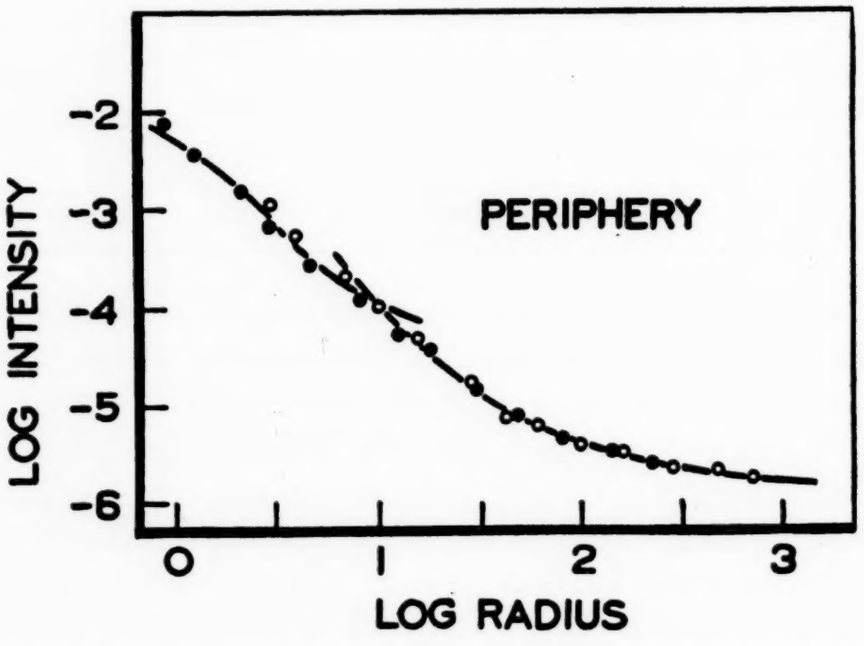

FIG. 2. The peripheral intensity threshold as a function of the stimulus radius. The right hand branch of the curve is computed from equation (6). The left hand branch has no theoretical significance. Equation (6) holds for areas having radii greater than 10 min.

the curve for the 70 cm observation distance. The averages of the two subjects are presented rather than the individual data. This seems legitimate since the agreement between the two subjects is good; the same form of curve describes the individual data as well as the average.

The relationships which are obtained between the intensity threshold and radius, as shown in Figs. 1 and 2 for the fovea and periphery, are similar in general outline to those which might be inferred from other investigations. With a small radius of exciting surface a high intensity is required to produce threshold and as the area increases the intensity requirement decreases. The curves for both fovea and periphery are not linear but decrease in slope as one progresses from the smallest area to the largest area. Figures 1 and 2 show that the intensity threshold decreases consistently throughout the limits of the areas used for both the fovea and the periphery. In both cases the threshold seems to approach a limiting, asymptotic value at the largest areas (Löhle, **23**).

The results are illuminating with regard to some findings of earlier workers. In the foveal curve of Fig. 1 the first four points may be roughly fitted by Ricco's Law, $AI = K$. In the peripheral results, Fig. 2, the same law may be used as a description of the points up to a log radius value of 1.5. Beyond these ranges both curves tend to have smaller slopes, and it is not surprising to find that over the medium range of peripheral areas Piper's law, $I\sqrt{A} = Constant$, might be considered to hold. The data for the largest areas are in accord with Löhle's conclusion that intensity finally becomes independent of area. This discussion shows again that all of these descriptions are empirical and have no validity for a curve which covers a large range of areas. A simple power function does not provide an adequate account of the area-intensity relation.

It is obvious that the significance of our results, particularly for the periphery, depends on their being obtained in a homogeneous part of the retina. If, for example, the thresholds for the rods vary in a systematic way from the center

of the eye to the periphery, then a decrease in threshold with an increase in area might only be due to the bringing in of more sensitive elements (Hecht, Haig and Wald, **16**). In order to test for the functional homogeneity of our peripheral region we performed several experiments of the same type. A single series will present the typical result.

The experimenter covered up the left half of the largest area (as viewed by the subject) and then determined 10 thresholds in succession for the resulting semicircle. Under these conditions only the temporal half of the stimulus circle was illuminated. Approximately 20 seconds elapsed between single threshold determinations. After this series was completed, thresholds were determined for the nasal half of the circle. The second series was followed by another on the nasal half and this in turn was followed by a series on the temporal half. A final series on the nasal half completed 50 threshold determinations. The results for each series, together with the average deviations of log I for each series, are presented in Table III. It will be noted in the table that

TABLE III

COMPARISON OF THRESHOLDS FOR THE TWO HALVES OF THE LARGEST AREA

Each intensity value is the average of 10 readings. Center of total stimulus circle 31.5° from fixation cross. Subject (CHG) completely dark adapted.

Order	Stimulus Semicircle	Log I (millilamberts)	A.D.
1	Temporal	−5.60	0.03
2	Nasal	−5.58	0.03
3	Nasal	−5.52	0.04
4	Temporal	−5.64	0.04
5	Nasal	−5.58	0.06

there is little difference between the thresholds for the two halves of the circle. The average deviations are small, and hence the thresholds are trustworthy. Since there seems, for all practical purposes, to be no differences between the thresholds for the two halves of the circle, we may conclude that we are dealing with a region in which no significant gradients of threshold sensitivity exist. A number of other experiments with smaller areas and under other conditions of presentation of stimuli verify this result.

Some Theoretical Considerations

An ultimately adequate theory of the area-intensity relation must account for the spatial effects which have been shown, by various techniques, to play a rôle in the vertebrate retina. Of these effects the most immediately important are those which have to do with spatial summation (Adrian and Matthews, **4**, **5**) and inhibition (Granit and Therman, **11**; Hartline, **12**). Needless to say, the precise mechanisms of the processes are obscure. The recent report by Hartline (**12**) which demonstrates a great diversity of action among the fibers of the vertebrate optic nerve, bears testimony to the complexity of the phenomena involved. For this reason, it would seem that, for the present, we should be satisfied with a tentative hypothesis which remains more or less at a flexible formal level, but which, nevertheless, has the virtue of presenting testable implications.

An old observation by Abney (**1**, quoted in **2**) points to an effect which may serve as an approach to the problem. Abney measured the extinction thresholds for areas of various sizes and from his observations made the following statement:

> The extinction of comparatively larger areas of light is most instructive. The light from a square, or a disc, or an oblong, just before extinction, is a fuzzy patch of grey, and appears finally to depart almost as a point. This can scarcely account for the smallest width of an illuminated surface determining the intensity of the light just not visible; but it tells us that the light is still exercising some kind of stimulus on the visual apparatus, even when all sensation of light is gone from the outer portions. . . . Supposing some part of the stimulus impressed on one retinal element did radiate in all directions over the surface of the retina, the effect would be greatest in its immediate neighbourhood and would be inappreciable at a small distance, but the influence exerted upon the adjacent element might depend not only on its distance, but also upon whether it was or was not itself excited independently. Following the matter out further, we should eventually arrive at the centre of an area, as the part which was the recipient of the greatest amount of radiated stimuli, and consequently that would be the last to disappear (**2**).

Abney's discussion emphasizes the spatial characteristics of visual stimulation, and its most important conclusion is to the effect that the greatest excitation occurs in the center of an area illuminated near threshold. This interpretation is in accord with the recent work of Hartline (**12**) on the receptive field of the single optic nerve fiber of the frog. The 'receptive

field' is the region of the retina which must be illuminated in order to obtain a response in any given fiber. For moderate intensities and small exploring points of light, the receptive fields of the fibers of the frog's eye are approximately circular, with a diameter of the order of 1 mm in the dark-adapted condition. This is probably greater than the diameter of the field for a single ganglion cell with its converging rods. In the receptive field, the strongest response is always obtained from the central region, while the response from the margins is usually of the threshold type.

The experiments of Hartline and Abney may involve a principle which explains the results of Adrian and Matthews (**4**) on the nerve discharge of the whole optic nerve of the eel. Adrian and Matthews found that, if area is increased, while intensity remains constant, the resulting nerve discharge shows a shortened latent period. This effect they attributed to summation in the synaptic layers of the retina. The results may be explained on the assumption, based on Abney's conclusion, that an increase in area results in a heightened degree of excitation of the neurones in the center of the stimulated area. This increased excitation causes a reduction in the latent period of the centrally placed neurones, and the effect is shown by an apparent reduction of the latent period of the discharge from the whole nerve.

It seems well established, in the light of the preceding discussion, that when an area of the retina is illuminated, the area does not exhibit a uniform degree of excitation in all of its associated nerve fibers. Rather, there seems to be a gradient of effect from the margin inward, the smallest degree of stimulation occurring in the outermost zones, while the greatest effect is in the center. Wald's recent account (**30**) of the area effect does not consider the question of a gradient, but since the concept clarifies certain issues we have used it as the basis of an alternative formulation.

Any quantitative account which we may give must be tentative and empirical so long as we do not know the equation for the gradient, but a simplification of ideas may be useful at a preliminary stage. Let it be assumed that the minimal

threshold is determined, in line with Abney's argument, at the center of a circular area. All other parts of the area are excited subliminally, but by the previous discussion will be making a contribution to the effect, E, at the center. Without regard to the precise mechanism of this effect, it may be accepted as an empirical approximation, that the excitatory contribution of an elemental area, $rdrd\theta$, to the threshold effect, E, at the center of the circle is inversely proportional to a power, p, of the distance from the center, r. Thus, excitatory contribution, dE, is proportional to $1/r^p$. Then with intensity constant the excitatory effect at the center will be

$$E = k_1 e \int_0^{2\pi} \int_0^R \frac{rdrd\theta}{r^p}, \tag{1}$$

where R is the radius of the circle, k_1 a constant of proportionality, and e a constant intensity effect in each elemental area. When light intensity varies e becomes a variable.

In the fovea the unit area may be thought of as being the single receptor cell, but in the periphery, with its summating groups of interconnected rods, a somewhat more complicated interpretation is necessary. In both cases e may be considered to be (1) the photochemical effect which takes place as a function of intensity in each receptor unit, or (2) the impulse frequency in the nerve fibers associated with the individual unit areas. For fovea and periphery, to a good approximation,

$$e = k_2 \log I/I_0, \tag{2}$$

where k_2 is a proportionality constant, I_0 the constant threshold intensity of the unit area (the sense cell or receptor unit) and I the intensity of incident light. The logarithmic relation has been shown to hold approximately for the photochemical effect by Hecht (**14**) and for the nerve impulse frequency by Hartline and Graham (**13**).

If we substitute $k_2 \log I/I_0$ for its equivalent, e, in equation (1) we get after integration,

$$E = cR^{2-p}(\log I/I_0), \tag{3}$$

where

$$c = \frac{2\pi k_1 k_2}{2 - p}.$$

The equation, in this form, might be expected to predict the type of result obtained by Adrian and Matthews (4). If intensity is maintained constant while the radius (or area) is increased, the right hand side of equation (3) increases, and hence E, the effect at the center, must increase. This could produce the shortening in a latent period of nerve discharge observed by Adrian and Matthews.

The simplest assumption which may be made with respect to threshold is that it is a constant effect. On this assumption, E, under conditions of our experiment is a constant, and equation (3) becomes

$$\log I/I_0 = CR^{p-2}, \tag{4}$$

where $C = E/c$. With the equation in this form we may test for the agreement between theory and data. Ordinarily, in order to evaluate constants, this has been done by taking logarithms on both sides of (4) in which case a plot of $\log \log I/I_0$ against $\log R$ should give a straight line with a slope of $p - 2$ and an intercept of $\log C$ if the theory fits the observations. The value of I_0 may be determined from a $\log I$ vs. $\log R$ plot; it is the asymptote of the curve on the $\log I$ axis. Specifically, it means that the thresholds for large areas approximate closer and closer to the threshold intensity of the elemental unit area (the sense cell or receptive unit). The constants determined for equation (4) in this manner result in the specific expressions

$$\log I/I_0 = 1.61R^{-0.51} \tag{5}$$

for the fovea, where $\log I_0 = -2.9$; and

$$\log I/I_0 = 6.92R^{-0.54} \tag{6}$$

for the periphery, where $\log I_0 = -5.95$.

The Quantitative Relations of the Data

The curve drawn through Fig. 1 represents equation (5) and the right hand branch of the curve in Fig. 2 represents equation (6). In Fig. 2, the curve for the smallest areas (left hand branch) has no theoretical significance.

Figure 1 and Table 1 show that equation (5) is a satis-

factory description of the foveal data. In Table 1 are entered the theoretical values of log I as calculated by equation (5). The only value which might be questionable is the point for the largest area. For this area, the theoretical value is slightly too large. With an area as large as this (diameter = 1°), it is reasonable to suppose that a good sampling of rods may be involved and such a conclusion is borne out by the histological findings of Rochon-Duvigneaud (**29**) which show that rods are present in the foveal area beyond the limits of the central bundle of cones. The central bundle comprises a distance on the retina of about 150 μ which corresponds to a visual angle of about 35 min. Further work (Graham and Bartlett, **10**), employing short flashes of red light for foveal stimulation, verifies the conclusion that the rods contribute to our results for the 1° area. With red light, which stimulates rods feebly, the data for a 1° area fall directly on the theoretical curve. For areas larger than a degree of diameter, the threshold probably decreases further due to the functioning of rods (Abney, **1**).

In Table 2 the values of log I calculated from equation (6) are presented for the peripheral data obtained at the observation distance of 70 cm. We have not made the calculation for the 230 cm distance, being content to show the agreement of observation and theory graphically in Fig. 2. Beginning at a radius of about 10 min (log R = 1.0) the experimental values fall close to the theoretical line. With small areas, however, there is a consistent increased deviation from theory as the areas become smaller and smaller. This deviation may be due to three causes: (1) Since neither photochemical effect nor frequency of nerve impulse is directly proportional to log I over a great range of intensities, we might expect a deviation from theory to occur at the high intensities necessary for the small objects in the periphery. In the fovea, since the intensity range is small in comparison with that in the periphery, the deviation would probably be insignificant. (2) It is undoubtedly true that the receptive unit of the periphery is not the single sense cell, but rather the ganglion cell with its many converging rod fibers. In this case, because

the receptive unit is not negligible in size, we should expect deviations from theory with the small areas, and this will be particularly true when we are working with areas smaller than the confines of the single unit. (3) It is possible that the peripheral cones are brought into play with the high intensities required for the small areas. This possibility may probably be dismissed on the basis of later work (Graham and Bartlett, **10**). With both violet and red light the curves appear similar to those of this experiment and the threshold is always colorless.

Of the causes for deviations noted above, (1) and (2) would have to be considered in any formulation which involved the idea of an excitatory gradient. The third cause probably may be ruled out on the basis of work to be reported (Graham and Bartlett, **10**). It will be necessary to consider the expression for e in equation (1) in greater detail in order to test for the non-linear relation between logarithm of light intensity and photochemical effect or nerve impulse frequency. We have made some calculations for the fovea in terms of Hecht's hypothesis (**15**) relating photochemical effect to intensity and find that when e is treated as a function of x, the concentration of photolytic products, the resulting expression describes our foveal data with considerable accuracy (Graham and Bartlett, **10**).

Discussion

Our experiments indicate what we believe to be the true relationship existing between intensity and the area of the stimulus for threshold excitation in the human eye. It is significant that when the determinations are sufficiently numerous and cover a large enough range of circular areas no simple power function of the form $A^kI = Constant$ can be considered an adequate description of the area-intensity relation in either the fovea or the periphery. The function relating $\log I$ to $\log A$ is a curve having large values of log intensity at small values of log area (or log radius). The log intensity values decrease along a smooth curve as area increases, until with quite large areas, the threshold intensity

values for both fovea and periphery are very nearly independent of area. It is only over restricted regions of the curve that a power function can be considered as in any way a satisfactory description of the relationship.

On the basis of certain theoretical concepts we have derived a quantitative account of some factors underlying the area-intensity relation. The description is built on the assumption that the threshold is determined by the centrally placed neurones which have the greatest degree of excitation because of the effects relayed from other more excentric regions. This account has certain advantages which have been pointed out. It explains the shortening of latent period of nerve discharge with increased area observed by Adrian and Matthews as well as the early observations of Abney on extinction thresholds, and as an explanatory principle it is in accord with the type of result observed by Hartline in the single fiber preparation of the vertebrate retina. The data for the fovea are accurately described by the theory over the range of areas which includes the rod-free zone and the data for the periphery are in agreement with calculation for areas which are no smaller in diameter than 20 min. A number of complicating factors which may arise below this limiting diameter have been discussed.

Summary

1. We have described an apparatus and procedure which made it possible to obtain reproducible intensity thresholds for varying sizes of illuminated areas in the human eye.

2. Intensity thresholds follow a typical course with an increase in area in both the periphery and fovea of the eye. In both regions the intensity threshold is high for small areas. As area increases, the threshold decreases until with large areas it approaches a final, limiting value.

3. In the fovea, the decrease of threshold with increase in area takes place within the confines of a stimulus diameter of about one degree. In the periphery, the final level is nearly attained at a diameter of 10 degrees.

4. A quantitative account of the area-intensity relation is

given. This describes the data over the total range of area in the fovea. In the periphery, it holds for areas having diameters greater than 20 minutes.

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THE RELATION OF SIZE OF STIMULUS AND INTENSITY IN THE HUMAN EYE: II. INTENSITY THRESHOLDS FOR RED AND VIOLET LIGHT[1]

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A recent paper from this laboratory (Graham, Brown, and Mote, **2**) has presented new data on the area-intensity relation for the fovea and periphery of the human eye and, in addition, puts forward a tentative theory of the effect. The experimental results of this earlier paper are concerned with white light, and the present report extends the analysis to the situation involving violet and red light. This has been done because of a question raised in the course of the previous work. The question is this: Are the systematic deviations from theory, which were found with small peripheral areas, due to stimulation of the peripheral cones by the high intensities required for threshold?

Hecht (**8**, **10**) has pointed out that a separation of rod and cone effects can be made on the basis of the differences in the visibility curves for photopic and scotopic vision. The difference between the cone threshold (photopic curve) and the rod threshold (scotopic curve) for violet light is very great, while with red light it is very small. Indeed, with extreme red light the difference may almost disappear, so that a dark adaptation curve measured with light of wavelength greater than about 630 mμ seems to represent cone function almost completely (Hecht, Haig and Chase, **9**).

The possibility of separating rod and cone functions by violet and red light relates to our experiment by the following argument: If peripheral cones are brought into play with a decrease in area and its concomitant increase in intensity,

[1] Supported by a grant from the Carnegie Corporation.

the effect should be visible for red at a larger area and lower relative intensity than it is for violet. Indeed, since the cone threshold for violet is 100 to 1000 times the rod threshold, we should be justified in expecting little or no cone activity to appear with this color. By the idea that red and violet light will influence the area-intensity relation differently depending upon their relative cone contributions, it may be expected that, if cones play a part, the area-intensity relation will exhibit a 'break' at the point where rod function passes to cone function. This break should occur at different places in the two curves and the rod and cone branches should cover different extents; hence the curves for red and violet light should not be parallel along the log intensity axis. Parallelism of the curves, on the other hand, may be accepted as good evidence that cone thresholds are not involved with either type of stimulation.

The results of our experiment show that the red and violet curves are parallel along the log threshold axis, and it is concluded that cones are not a factor in the peripheral determinations. Further experiments on the fovea with red light show good agreement with the theory developed by Graham, Brown and Mote, and in the present paper the theory is amplified to relate it to some of the more recent developments (Hecht, **8**) in the photochemistry of vision.

Method

The method and apparatus of the present experiment are similar to those of the earlier experiments with these exceptions: (1) the threshold stimulus is now either red or violet light and (2) its exposure is restricted to a duration of 12.8 milliseconds.[2] Red light is provided by the use of Wratten monochromatic filter 70 (central wavelength about 680 mμ) and violet light by Wratten filter 76 (central wavelength about 445 mμ).

For the peripheral determinations the subject regards the red foveal fixation cross of the previous experiment from a distance of 62 cm. Observation is with the left eye. The threshold stimulus area appears to the right of the fixation cross along the horizontal axis, and its center is at a visual angle of 15° from the center of the cross.

For the foveal determinations we have used the fixation device previously described (2). This is an apparatus so contructed that to the subject it appears as a rectangular, dimly illuminated background, in the center of which is a circular, black expanse. In the determination of thresholds, the stimulus area appears in the center

[2] This is the total duration of the flash. Of this duration 3.1 milliseconds are required for the light to reach full intensity and 3.1 milliseconds for it to sink to zero. Thus, the full intensity is on for 6.6 milliseconds.

of the black circle. A precise description is contained in the earlier paper, and the advantages of the method are pointed out. The fixation distance for foveal determinations is 220 cm, and observations are made with the left eye. We did not use artificial pupils in any of the experiments, since the eye was in a constant state of adaptation at the moment of each determination, and since the duration of threshold flash was well within the latent time of the pupil.

The only modification in the optical system of the previous experiment entails the use of a shutter to restrict the duration of the threshold flash. The shutter consists of a phonograph motor, to the axle of which is attached a large disk. A slit cut near the periphery of the disk allows for the control of duration of flash. In order to restrict the illumination to single flashes, a hand-operated shutter is placed in the optical path. A flash is let through to the stimulus screen only when the hand-operated shutter is released and the duration of flash is determined by the size of the slit in the disk of the motor (Graham and Kemp, 3). A system of lenses introduced into the beam brings the light to a focus in the plane of the slit. From there the rays diverge and, after passing through (1) a holder for Wratten neutral tint filters and a Wratten monochromatic filter, and (2) a wedge and balancing wedge, finally emerge to illuminate the opal-glass surface. For certain of the determinations an additional lens may be interposed between the balancing wedge and the opal glass.

In the experimental series on the periphery the subject[3] was given a half-hour's dark adaptation before any determinations were made. At the end of this interval a threshold measurement was made for a particular stimulus area by the experimenter who set the wedge for an intensity well below threshold and allowed a flash of light to pass the shutter. After the subject's report the wedge was moved a distance of about 5 mm. and another flash was let through after about 15 seconds. This procedure was continued until the subject reported that he saw the light. The threshold was accepted as the intensity which was first seen in this ascending procedure. Two such determinations were made and then the stimulus area was changed. Each day's run involved determinations on all twenty-two areas and the order of presentation was similar to the one used by Graham, Brown and Mote. A complete experiment for each subject and color consisted of four complete series on all the stimulus areas.

The procedure in the foveal series was similar to that used in the peripheral series. Any day's run involved all eleven areas and four such runs were made with each subject, two determinations being made on each area on a given day. Adaptation conditions were as reported in the first paper of the series (2). The subject was given 15 seconds of light adaptation and this was followed by 105 seconds of dark adaptation for each area. At the end of the dark adaptation period threshold measurements were made by the ascending procedure described for the periphery. Observations were with the left eye. Red light only was used in this experiment and the brightness of the light-adapting screen (white light) was 350 millilamberts.

Results

The results on the fovea[4] for subjects V and G are presented in Table I and Fig. 1*A*. The general relationship

[3] We are greatly indebted to Miss Virginia G. McGann and Mr. W. S. Verplanck for many hours of tedious observation. Subject G is one of the authors (CHG).

[4] The intensity values in millilamberts were determined with the violet and red filters by heterochromatic photometry against white light with the light adapted fovea. These intensity values are the ones presented for both fovea and periphery.

TABLE I

INTENSITY THRESHOLDS FOR DIFFERENT AREAS OF STIMULUS IN THE FOVEA
Red light (Wratten filter No. 70). Subject at distance of 220 cm. Intensity readings in millilamberts; radius values in minutes of visual angle.

Radius (min.)	Log Threshold intensity	
	Subject V	Subject G
1.0	0.159	0.164
1.3	$\bar{1}$.949	$\bar{1}$.951
1.75	$\bar{1}$.762	$\bar{1}$.729
2.25	$\bar{1}$.619	$\bar{1}$.509
3.25	$\bar{1}$.372	$\bar{1}$.287
4.10	$\bar{1}$.189	$\bar{1}$.112
5.50	$\bar{1}$.074	$\bar{2}$.954
8.75	$\bar{2}$.979	$\bar{2}$.824
13.30	$\bar{2}$.689	$\bar{2}$.597
18.10	$\bar{2}$.569	$\bar{2}$.469
31.2	$\bar{2}$.489	$\bar{2}$.379

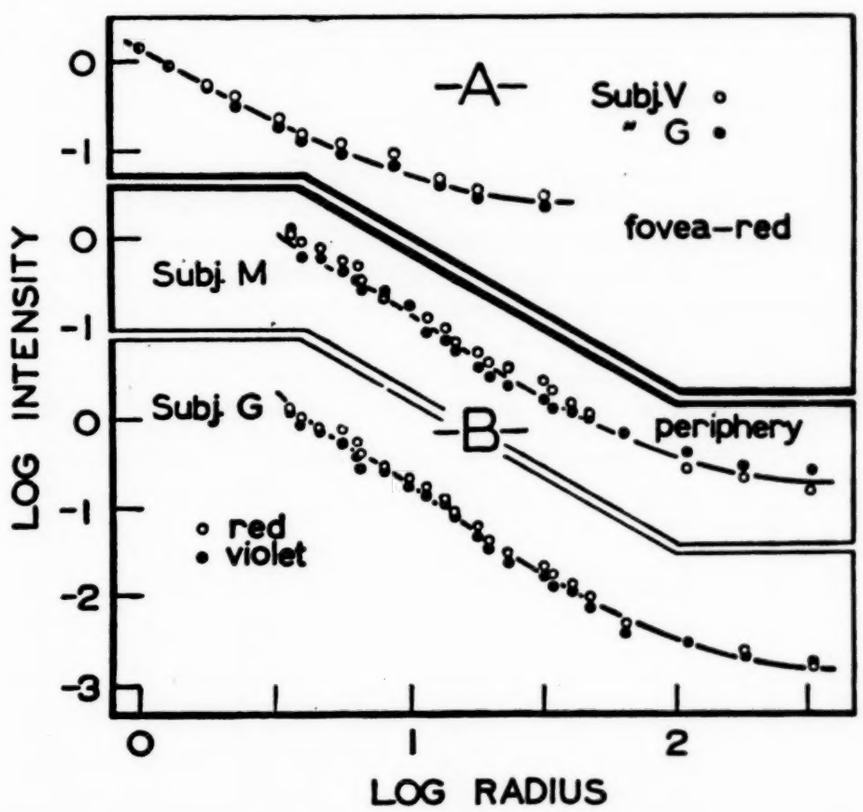

FIG. 1*A*. Log intensity threshold for red light as a function of log radius for subjects V and G. *B*. Thresholds for red and violet light for the periphery. The data for violet have been displaced upwards on the graph for each subject as described in text. Subjects M and G.

shown in Fig. 1*A* is similar to the one obtained with white light (Graham, Brown and Mote, **2**). As area increases, the threshold intensity decreases more and more slowly through-

out the extent of the rod-free area, *i.e.*, up to a visual angle of somewhat more than half a degree (Rochon-Duvigneaud, 11). In the earlier paper the final experimental point at a radius value of 30 min seems to fall below the smooth curve of the rest of the data. The corresponding value of the present experiment (31.2 min) does not do this, a fact which we attribute to the small difference in rod and cone thresholds for red light. Presumably, with areas which would involve a great number of rods the threshold with red light would continue to drop. This is the type of result obtained by Abney (1) who found a decrease in threshold for central areas extending up to a limit of 4 degrees.

Results of the peripheral determinations are presented in Table II. The two curves of Fig. 1*B* show the general form

TABLE II

INTENSITY THRESHOLDS FOR RED (WRATTEN FILTER 70) AND VIOLET (WRATTEN FILTER 76) LIGHT IN THE PERIPHERY

Subject at distance of 62 cm. Intensity readings in millilamberts; radius values in minutes of visual angle.

Radius	Subject M		Subject G	
	Violet log *I*	Red log *I*	Violet log *I*	Red log *I*
3.66	$\bar{4}.79$	0.06	$\bar{3}.00$	0.14
4.00	$\bar{4}.50$	$\bar{1}.97$	$\bar{4}.87$	0.03
4.82	$\bar{4}.48$	$\bar{1}.89$	$\bar{4}.80$	$\bar{1}.94$
5.54	$\bar{4}.34$	$\bar{1}.78$	$\bar{4}.64$	$\bar{1}.89$
6.20	$\bar{4}.22$	$\bar{1}.70$	$\bar{4}.49$	$\bar{1}.78$
6.66	$\bar{4}.13$	$\bar{1}.55$	$\bar{4}.37$	$\bar{1}.66$
7.83	$\bar{4}.10$	$\bar{1}.36$	$\bar{4}.35$	$\bar{1}.50$
9.79	$\bar{5}.96$	$\bar{1}.25$	$\bar{4}.17$	$\bar{1}.37$
11.55	$\bar{5}.66$	$\bar{1}.12$	$\bar{4}.07$	$\bar{1}.24$
13.48	$\bar{5}.57$	$\bar{1}.01$	$\bar{5}.98$	$\bar{1}.12$
14.55	$\bar{5}.45$	$\bar{2}.84$	$\bar{5}.85$	$\bar{1}.01$
17.55	$\bar{5}.26$	$\bar{2}.72$	$\bar{5}.62$	$\bar{2}.86$
19.55	$\bar{5}.13$	$\bar{2}.62$	$\bar{5}.49$	$\bar{2}.71$
24.10	$\bar{5}.04$	$\bar{2}.55$	$\bar{5}.35$	$\bar{2}.58$
31.23	$\bar{6}.90$	$\bar{2}.40$	$\bar{5}.19$	$\bar{2}.39$
34.00	$\bar{6}.81$	$\bar{2}.32$	$\bar{5}.09$	$\bar{2}.31$
39.45	$\bar{6}.77$	$\bar{2}.18$	$\bar{5}.02$	$\bar{2}.20$
47.20	$\bar{6}.69$	$\bar{2}.05$	$\bar{6}.83$	$\bar{2}.03$
63.62	$\bar{6}.54$	$\bar{3}.83$	$\bar{6}.58$	$\bar{3}.76$
110.8	$\bar{6}.33$	$\bar{3}.46$	$\bar{6}.43$	$\bar{3}.43$
175.9	$\bar{6}.21$	$\bar{3}.35$	$\bar{6}.29$	$\bar{3}.44$
300.7	$\bar{6}.18$	$\bar{3}.23$	$\bar{6}.19$	$\bar{3}.24$

of the relation existing between log threshold intensity and log radius. The ordinate values refer to red light; the values for violet light have been moved upwards along the ordinate, in the case of Subject M, through a distance of 3.3 log units and, for Subject G, through 3.1 log units. (A further shift through 0.1 log unit would give better coincidence of the curves for both subjects, but the indicated distances are used for convenience in graphing.) The curve drawn through the data for each subject indicates that a single function varying only in the value of a vertical scale constant describes the results.

The curves of Fig. 1*B* portray the same type of relationship between intensity and area as was demonstrated in the earlier paper (**2**). With small areas (or radii) a high intensity of illumination is required to produce threshold. As the area increases, the intensity requirement becomes smaller and eventually the curve reaches a final limit at which, with large areas, the intensity threshold is independent of area. Parallelism of the curves is demonstrated by the procedure of shifting the violet curve until it coincides with the red. This means that the functions for the two colors differ only in a scale constant which contains the visibility coefficient. Beyond this, the curves exhibit nothing which could be attributed to a difference in rod-cone contribution; they are parallel throughout and their component branches show no differences in extent.

Earlier in the paper we pointed out that parallelism of the curves would exclude the possibility that cone thresholds are involved. Because of the clear-cut evidence of parallelism now presented, it would seem that the deviations from theory with small areas are not due to the functional admixture of cones. This conclusion is strengthened by the fact that the subjects always reported an absence of color at threshold.

Theoretical

The theory put forth in the previous paper (**2**) is based on the idea that the excitatory contribution of any element of area in polar coördinates, $rdrd\theta$, to the threshold effect, E,

at the center of the circle of excitation is inversely proportional to a power of the distance, r, from the center of the circle. Thus, dE is proportional to $1/r^p$ and the expression for the excitatory effect at the center is

$$E = k_1 e \int_0^{2\pi} \int_0^R \frac{r dr d\theta}{r^p}, \tag{1}$$

where k_1 is a constant of proportionality, e the excitatory effect in each element of area, and R the radius.

As a good approximation we have considered that $e = k_2 \log I/I_0$, where I_0 is the threshold intensity of the single receptive unit. This relation is in accord with the fact that, over considerable ranges of intensity, photochemical effect (Hecht, **6**) and frequency of nerve impulses (Hartline and Graham, **5**) are proportional to the logarithm of light intensity. When $k_2 \log I/I_0$ is substituted for e in equation (1) our expression becomes

$$E = c' R^{2-p} (\log I/I_0), \tag{2}$$

where

$$c' = \frac{2\pi k_1 k_2}{2 - p}.$$

In the present experiment, we are concerned with a threshold effect, E, which may be considered constant, and hence equation (2), for this special case, is written

$$\log I/I_0 = C R^{p-2}, \tag{3}$$

where $C = E/c'$.

It has been pointed out (Graham, Brown, and Mote) that if equation (3) be a valid description of data, a plot of $\log \log I/I_0$ against $\log R$ should give a straight line whose slope is the constant, $p - 2$, of equation (3). In this treatment, I_0 is the intensity asymptote for large values of R.

The curves of Fig. 2 indicate the agreement between the theoretical prediction and the results of the experiments. In constructing the graph for the fovea (curve F–R), the I_0 value was determined for each subject independently and the $\log I/I_0$ values averaged. This seems legitimate in view

of the fact that the shapes of the individual curves for subjects V and G are similar. This procedure was repeated for the data of the two subjects, M and G, on the periphery, and the curves (P–R) and (P–V) of Fig. 2 present the results for red and violet respectively.

In Fig. 2 it may be observed that the theoretical fit for the foveal data is good. The line drawn through the experimental points has a value of -0.5 for the slope constant, $p - 2$, which is to be contrasted with the value of -0.51 found for white light by Graham, Brown and Mote. The curves drawn through the points for the peripheral data have

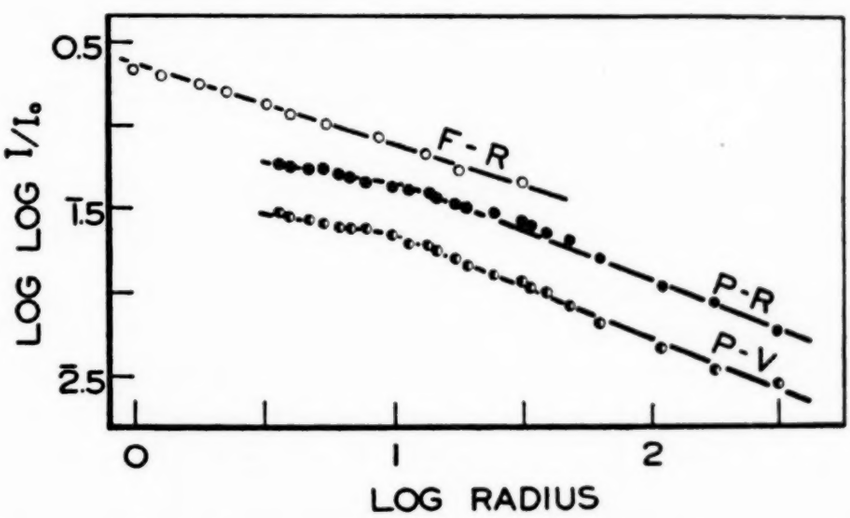

FIG. 2. Theoretical plot of the data for the periphery and fovea in terms of equation (3). Curve F–R, data for stimulation by red light in the fovea; curves P–R and P–V, data for red and violet respectively in the periphery. Curve P–R has been displaced downward along the ordinate axis through 0.75 log unit. Curve P–V has been similarly moved through 1.00 log unit.

a slope of -0.6 for log radius values greater than 1.0. This is to be compared with the slope of -0.54 for the corresponding range of radii in the experiment on white light. The results on small areas for the peripheral red and violet are similar to those obtained previously. Below a value of $\log R = 1.0$ the peripheral curves of Fig. 2 show a decreased slope and it is clear that equation (3) does not describe the results for very small areas. Reasons for this failure have been discussed (2).

The Area Effect and Photochemical Theory

The treatment embodied in the graphs of Fig. 2 shows that the theory developed for white light holds adequately for red and violet light. As developed up to the present, the hypothesis is based on the notion that the excitatory effect, e, in any element of area, $rdrd\theta$, is proportional to log I.

It does not require a great extension of this idea to consider that the elemental excitatory effect, e, is a function of the concentration of photoproducts, x (Hecht, **8**). This interpretation is particularly urgent when it is remembered that, over a wide range of light intensity, the concentration of photoproducts is proportional to log I. In order to test our data in terms of photochemical theory it is necessary to consider how such a treatment might relate to the conditions of our experiment.

According to Hecht's interpretation (**6**), the photoreceptor process is composed of two parts: a primary photochemical system and a secondary 'dark' system. Wald's analyses (Wald and Clark, **13**) indicate the presence of more complex factors, but these may be overlooked in the present experiment since we are using flashes of very short duration, 12.8 milliseconds. Under the condition of using a short flash, the 'dark' reaction is probably not effective (Hartline, **4**) and we may write that

$$\frac{dx}{dt} = k_1 I(a - x)^m. \tag{4}$$

This equation states that the rate of photochemical decomposition is proportional to the product of the incident intensity and the concentration of sensitive material. In this equation, x is the concentration of photoproducts broken down by the light, I, t is time, a is the total initial amount of photosensitive material, m is the order of the reaction, and k_1 the velocity constant.

For very short durations of exposure, photolysis takes place almost instantaneously and the total amount of x is formed in the interval taken up by the flash. If the flash

has a duration, τ, we may restate equation (4) approximately as

$$\frac{x}{\tau} = k_1 I(a - x)^m, \tag{5}$$

where the symbols have the same significance as in the previous equation. Where the duration of flash is constant, as in the present experiment, equation (5) becomes

$$kI = \frac{x}{(a - x)^m}, \tag{6}$$

in which $k = k_1\tau$. Equation (6) is identical in form with some of Hecht's stationary state equations (8). When $m = 1$, the curve of equation (6) is similar to his 1, 1 curve; and when $m = 2$ it is comparable to the 2, 1 curve. As developed by us the equation merely states the order of the forward reaction. For the monomolecular case, $m = 1$, and for the bimolecular, $m = 2$. As with Hecht's stationary state equations, $\log x$ [calculated by equation (6) with $m = 1$ or $m = 2$] may be plotted against $\log I$, in which case the shape of the resulting curves is independent of the value of k or the unit of x.

In order to test our ideas with regard to the photochemical aspects of our problem, it is necessary to derive an expression in which x is related to the variables of this experiment, *i.e.*, intensity or area. This may be done if we consider that e in equation (1) is a function of x. One can make the simple assumption that e is proprotional to x; but, in addition, it must be remembered that the unit receptive area requires a threshold, x_0. For this reason e is considered to be proportional to $x - x_0$, and equation (1) becomes

$$E = k_3(x - x_0)\int_0^{2\pi}\int_0^R \frac{r\,dr\,d\theta}{r^p}, \tag{7}$$

where k_3 is a constant of proportionality. On integration this gives

$$E = \frac{2\pi k_3}{2 - p}(x - x_0)R^{2-p} \tag{8}$$

and for threshold, where E is constant,

$$\frac{x}{c} = R^{p-2} + \frac{x_0}{c}, \tag{9}$$

where

$$c = \frac{(2 - p)E}{2\pi k_3}.$$

Equation (9) gives us an expression for x in terms of one of our experimental variables, R, and allows us to test our data in terms of the implications of equation (6). As an approximation we may consider that the values of $p - 2$ for the fovea and periphery are -0.5 and -0.6 respectively, as in Fig. 2. The value of c in (9) is of no immediate significance since it only determines the unit of x in the $\log x$ vs. $\log I$ graph. This leaves only x_0/c to be evaluated. If this be determined, one may plot values of $\log x$, in terms of c as the unit, against the corresponding log threshold intensities for the various values of R, and observation should reveal which form of equation (6) fits the data. In this type of graph neither the constant c of equation (9) nor the constant k of equation (6) has any influence on the shape of the resulting curves.

This test has been made in Fig. 3, where the values of $p - 2$ are -0.5 for the fovea and -0.6 for the periphery. In both cases x_0/c has been given a value of 0.01. The curve drawn through the data for both regions of the retina is calculated from equation (6) with $m = 2$. Clearly, the fit for the fovea (curve F–R) is good, and on the basis of our reasoning we may be justified in considering that the 'light' reaction in the region of the retina is bimolecular in nature.[5] This is in accord with interpretations as to the photochemical mechanisms of a number of other foveal functions: *e.g.*, intensity discrimination (Hecht, 7), flicker

[5] We have tried to fit a number of other curves to the data including the one involving $m = 1$. So far as we can see the only formulation which at all adequately fits the data is the one presented here. The value of $x_0/c = 0.01$ is quite critical for the periphery. For the fovea it is not so critical; the fit seems to be nearly as good when x_0/c has a value of zero. This may mean that the threshold value of x for the fovea is a very small percentage of the total supply.

(Hecht and Shlaer, **10**) and acuity (Shlaer, **12**). The fit for the red and violet peripheral data (curves *P–R* and *P–V*) is not so satisfactory. The bimolecular curve fits the branch for areas greater than log R = 1.0 fairly well, but it departs from the data in an unequivocal manner for the small areas and high intensities. This is the type of result obtained with the simpler theoretical statement in which $e = k_2 \log I/I_0$, and the present treatment in no way increases the adequacy of the fit. This failure may exclude one possible explanation

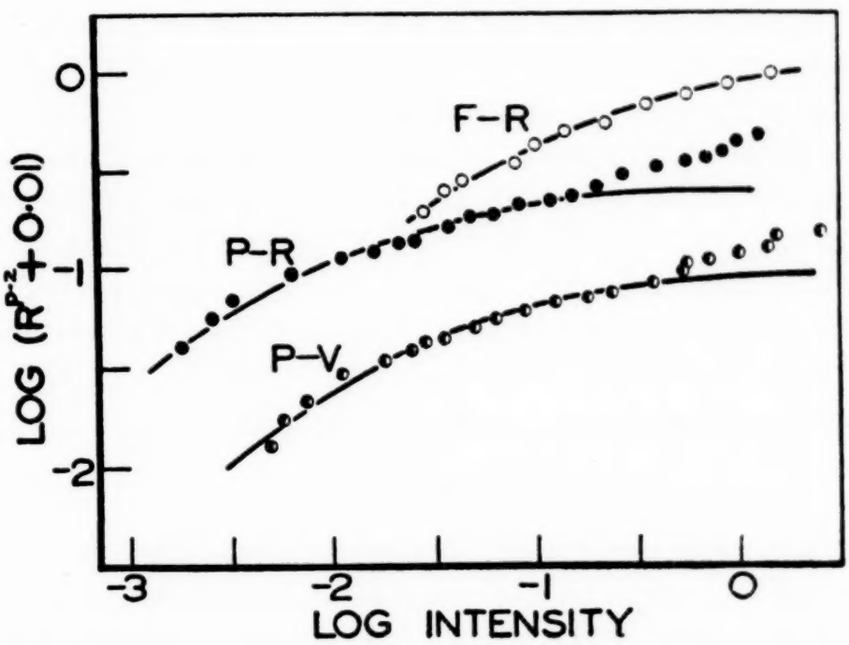

FIG. 3. Theoretical plot of the foveal and peripheral data in terms of equation (6) with m = 2. Curve *P-V* (peripheral stimulation by violet) has been moved 3.5 log units to the right and 0.5 log unit downwards along the ordinate for convenience in graphing.

of the discrepancy, at small areas, between theory and experimental result. Graham, Brown and Mote emphasize that photochemical effect is not strictly proportional to log I over a great range of intensities and that deviations from a theory based on this approximation would be greatest with the high intensities necessary for small areas. The present calculations indicate that the more exact formulation has no superiority in this matter.

The experimental part of this report on the comparison of

thresholds for violet and red light seems to dispose of another possible explanation for the deviation, *i.e.*, that it is due to the activity of cones. We have earlier discussed this point in considerable detail and it would seem that the evidence for parallelism of the curves for red and violet is clearly against such a possibility. A more immediately acceptable basis has been discussed in the first paper (Graham, Brown and Mote, **2**) and concerns the fact that the receptive unit of the periphery is not the single sense cell, but rather the ganglion cell with its many converging rod fibers.[6] Because of this, we might reasonably expect deviations from theory with the small areas and this will be particularly true when we are working with areas smaller than the confines of the single unit. Ultimately, it may be required that the hypothesis advanced here take account of the limits of the receptive unit. Undoubtedly this would contribute greater generality and accuracy, but the theory, even as it is now stated, is adequate for the spatial limits ordinarily encountered and holds for wider ranges of area than any of the well-known empirical laws, *e.g.*, Ricco's or Piper's.

Summary

1. We have determined intensity thresholds for red and violet light as a function of the area of the stimulating surface for the periphery of the human eye. Measurements with red light were made on the fovea.

2. Under the conditions of stimulation used in this experiment the intensity thresholds for both fovea and periphery follow a typical course with an increase in area. The intensity threshold is high for small areas and decreases as area increases, until with larger areas it approaches a final, limiting value.

3. The curves obtained on the periphery for red and violet are parallel along the log threshold axis. This is

[6] Another possibility, heretofore unmentioned, concerns the effect of the halo of scattered light in the periphery which might be expected to occur most importantly with small areas and high intensities. It is difficult to evaluate the magnitude of this effect, but other experiments in which a surround is used might shed some light on this question.

interpreted to mean that no cones are involved with either type of stimulation.

4. The results are described by an hypothesis developed in an earlier paper (**2**) and by one which considers the photochemical activity of the single retinal receptive unit.

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VISUAL ACUITY IN THE PIGEON [1]

BY RAY D. CHARD

From a consideration of the performance of pigeons in homing it is evident that their vision must provide significant and important cues for proper orientation (**30**, **5**, **6**). Accordingly, an accurate knowledge concerning their visual acuity might indicate the limits of usefulness of visual cues. The aim of the present experiment, therefore, was to determine the thresholds of acuity for pigeons at various accommodation distances.

We know that the range of the spectrum in pigeons coincides with that of man (**31**). Pigeons are only slightly less sensitive than man to differences in wave-length over the regions of the spectrum from 711 to 460 mμ., and their hue discrimination curve is of the same form as that of man, having points of low threshold in the yellow and blue-green regions (**11**). The mechanism for accommodation and pupillary response is extremely rapid. Accommodation probably involves changes in corneal curvature, position of lens, and lens curvature (**9**). Structurally the eye is highly differentiated and there is every indication that it is a visual organ of great excellence. The eye is large. It has a well-defined fovea and area centralis. The retina is thicker than that of man, and there are no retinal blood vessels to interfere with vision. All internal muscles of the eye are striated, thus providing for rapid responses (**2**).

Various writers have proposed different definitions of visual acuity. The term appears to refer to four general types of sensitivity depending on the stimulus object used in measurement of the eye.

1. *Minimum separable acuity* is the measurement of the

[1] From the Psychological Laboratory of Princeton University.

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smallest amount of separation necessary to perceive two points as discrete entities. Stimuli used for measuring it include two points, two lines, groups of lines (gratings or striæ), the E-shaped figure of Snellen, and the Landolt 'broken circle.' In animals determinations of minimum separable acuity have been made, traditionally, by having the animal react to striated stimulus objects composed of black lines separated by white interspaces. The lines and interspaces are equal in width.

2. *Minimum visible acuity* is the measurement of the visual angle subtended by the smallest object (point or line) that can be distinguished from its background. In a determination of minimum visible acuity the animal reacts either to the direction of a single line, or a few lines widely spaced on a high contrast surface; or it reacts to the presence or absence of lines (single, or widely spaced) on a field.

3. *Vernier or displacement acuity* is the measurement of the threshold of lack of alignment between two straight lines placed end to end.

4. *Stereoscopic acuity* is the fineness of depth perception.

Animal studies have been limited to a determination of either minimum visible acuity or minimum separable acuity. The two types of acuity have recently been regarded as dependent on the same processes (**32**). Nevertheless, in man, determinations of minimum separable thresholds vary between 1 and 0.5 min. (**32**) while minimum visible thresholds are given at 0.066 min. (**13**). In preliminary work with the pigeon we found evidence of minimum visible discrimination at 1.52 min.; the minimum separable was higher. Since minimum separable acuity would seem to be of greater importance in pattern vision the present study has been limited to this aspect of sensitivity.

The methods for testing acuity in animals have generally followed three lines, (1) the Yerkes-Watson discrimination box in various forms, (2) the jumping reaction, and (3) reflex responses to visual stimulation.

Casteel (1) trained two turtles in a modified Yerkes-Watson box to discriminate horizontal from vertical lines of

the same width. The turtles learned to react correctly to lines 8 mm wide. With lines of 2 mm width the animal's performance was still slightly better than chance. Unfortunately, Casteel did not state the angle subtended by these lines, since he was not interested in a determination of the threshold of acuity.

H. M. Johnson (**16**, **17**, **18**, **19**) was the first to establish thresholds of acuity in animals. In his work on pattern discrimination in vertebrates he used a standard Yerkes-Watson discrimination box suitably modified to conform to the species used. Two methods of testing were used. Under one set of conditions the field of one stimulus object was composed of striæ so small that probably they appeared as a homogeneous plain field to the animal. The other field had wide stripes that were reduced in size until the discrimination broke down. In the second method, the striæ were exactly the same for both fields, but in one the lines were horizontal, and in the other they were vertical. The animal was trained to react to the direction of the lines. For the chick, with the first method, the threshold was 4.07–4.23 min.; for the monkey it was found to be 0.95 min. He was not able to obtain a measurement of the acuity of the dog by these methods.

Johnson concluded ". . . that uncertainty in choosing begins at nearly the same absolute stimulus-value whichever method is used" (**19**, p. 200). However, Gundlach (**7**) in discussing Johnson's results, pointed out that there is a difference in results for the two methods. The first method appears to be the easier since with it two birds learned in 443 and 214 trials respectively, but when the lines differed in direction only, one bird failed to learn and the other took 588 trials.

Gundlach (**7**), by means of a modified Yerkes-Watson discrimination apparatus, and after laborious training, obtained thresholds of 0.38 and 0.50 min. respectively for two pigeons. Smith (**25**), working with cats, obtained successful discrimination of parallel striæ subtending an angle of 5.5 min. Finer discriminations were not studied with striæ. Spence

(**24**) [2] obtained a threshold of 0.47 min. for the chimpanzee.

In 1930 Lashley (**21**) definitely demonstrated that earlier failures to get clear-cut evidence of detail vision were products of the method used. When testing rats with the discrimination box (**20**) he was able to get differential reactions to the direction of lines, but could not get the rats to discriminate other patterns. When he used another apparatus, involving a jumping response, there was little difficulty in training the animals, and they showed a high order of pattern discrimination.

Graham and Nafe (**4**) tested brightness discrimination in four human subjects on a Yerkes-Watson apparatus and compared curves derived from this method with the standard Koenig-Brodhun curves. The results showed that brightness discrimination was very poor in the Yerkes-Watson apparatus as compared with the standard curves. They conclude that the large difference which they found is due to the method and apparatus, and maintain that the Yerkes-Watson box should not be used if a more refined method is available.

Graham and Nafe believe that three factors must be controlled to get thresholds on animals comparable with those on human beings. First, the eye position should be systematically varied and so controlled that head movements do not change either the situation or the state of accommodation and convergence. Second, the nature of the stimulating conditions is important. In the apparatus usually used in human work the stimuli to be compared are juxtaposed, but in the Yerkes-Watson apparatus they are separated, and in some modifications the two stimuli must be viewed in successive fixations. Separation makes discrimination more difficult, but it is not known how much various distances of separation affect it. Finally, there is the matter of the simplicity of the required response. Graham and Nafe state, "This element is not one which is obvious, but is one worthy of consideration. The question must often arise in animal work as to whether

[2] The apparatus of Spence involved a considerable modification of the Yerkes-Watson box. The subjects reacted to the stimuli by reaching into a box under the appropriate stimulus to obtain food.

certain 'irrelevant' features of the situation are not acting as conditioning stimuli on the organism. If this is the case, the animal has to learn to eliminate responses to all but the relevant features. It is questionable whether in all cases the animal does this. One of the possible results is that discrimination may be inaccurately measured" (4, p. 229).

The improved apparatus of Lashley corrects some of the inherent difficulties of the Yerkes-Watson apparatus. The animal is required to jump from a circular platform directly *against* the stimuli. In a correct response the stimulus card is knocked down by the animal. This arrangement allows it to gain entrance to a shelf behind the card on which food is placed. The animal is punished for an incorrect response, since, in this case, it jumps against an immovable card and falls into a net placed below.

The jumping method does not entirely control head position but it somewhat limits this variable. The stimuli are separated slightly, but both can be observed at the same time. In the control of the third factor indicated by Graham and Nafe probably lies the virtue of the jumping technique. The animals have to respond *directly* to the stimuli and the effect of 'irrevelant' stimuli which might prove distractions is reduced to a minimum. Furthermore, the animal is rewarded or punished immediately after jumping.

Only two studies of acuity have been made by means of this technique. Lashley (**22**) found the threshold for pigmented rats to be between 52 and 26 min. of arc; that of albinos was 2 to 4 times higher. Hamilton and Goldstein (**12**) found the acuity of the pigeon to be from 2.7 to 3.8 min. The latter work will be discussed in detail below.

A reflex method has been developed recently by Smith (**26**) in the study of visual responses in vertebrates. With this method a field of vertical lines is moved around the animal to be tested. The responses to the moving stimuli are forced movements of the eyes, head, and body.[3] Warken-

[3] An excellent summary concerning the nature and significance of these responses in mammals has recently been published by Smith and Bojar (**27**). The discussion in this paper is limited to the reflex responses of vertebrates. However, it should be

tin (**28**, **29**) applied the method to a study of the acuity of several vertebrate forms. Most determinations were for minimum visible acuity and therefore will not be presented here. His measurements of minimum separable acuity appear in Table 1.

Luckiesh and Moss (**23**) have shown that, in man, visual acuity is dependent on the amount of accommodation in force, and decreases as the latter increases. Gundlach (**7**) removed his test fields 20 feet from the point of choice to in-

TABLE 1

MINIMUM SEPARABLE THRESHOLDS OBTAINED BY VARIOUS INVESTIGATORS WHO TESTED VISUAL ACUITY IN ANIMALS BY MEANS OF STRIÆ

The methods used have been designated at the extreme right as 'Yerkes-Watson,' 'jumping,' and 'reflex'

Investigator	Animal	Threshold in Min.	Accommodation Distance in cm	Method
Hartridge (13)...	Human adult	0.80–1.06	—	—
Wilcox and Purdy (32)....	Human adult	0.50–1.0	—	—
Spence (24).....	Child	0.62	120	Yerkes-Watson
	Human adult	0.44	120	Yerkes-Watson
Spence (24).....	Chimpanzee	0.47	120	Yerkes-Watson
Johnson (17).....	Monkey (Cebus)	0.95	60	Yerkes-Watson
	Human adult	0.82	60	Yerkes-Watson
Lashley (22).....	Rat (albino)	52–86	20	Jumping
Lashley (22).....	Rat (pigmented)	26–52	20	Jumping
Johnson (17).....	Chick	4.07–4.23	60	Yerkes-Watson
Gundlach (7)....	Homing pigeon	0.38–0.50	599.6	Yerkes-Watson
	Human adult	0.83–1.00	599.6	Yerkes-Watson
Hamilton and Goldstein (12)..	Pigeon	2.70–3.80	107–31	Jumping
Warkentin (29)...	Opossum	11.00	50	Reflex
Warkentin (29)...	Alligator (in fall)	11.00	50	Reflex

sure distance accommodation. Hamilton and Goldstein (**12**) submitted evidence purporting to show that acuity was poorer at 31 than at 66 cm, and concluded that the near-point of accommodation lies at some point between these two distances. Smith (**25**) obtained the lowest threshold of acuity for the cat at 75 cm. At distances greater or smaller than this

stated that Hecht and his co-workers (**14**, **15**, **33**) have tested acuity in some invertebrates by a similiar method. This method has been adapted by Graham and Hunter (**3**) for use with human subjects.

the visual acuity was less. Thus, there is evidence that accommodation is an important factor to be considered in studies of animal acuity.

Table 1 summarizes the results of various studies of visual acuity in vertebrates which utilize striæ as stimulus objects. These are minimum separable thresholds. In each case the method of testing has been designated at the extreme right of the table. Accommodation distances are also given.

The Yerkes-Watson type of apparatus requires laborious training and has given equivocal results. The reflex method has been used mainly to determine minimum visible thresholds, and the functioning of various visual centers in the central nervous system. Since the optokinetic response may exist in the absence of a striate cortex, and since the removal of the striate cortex produces complete and permanent blindness to patterns, there is a question whether such a response is of the same nature as a discrimination response requiring the animal to make a choice between two or more patterns.

In the present investigation it seemed advantageous to use a modification of the jumping technique which would allow tests to be made at various accommodation distances.

Apparatus and Procedure

The apparatus used in the present study was a modification of that of Halstead and Yacorzynski[4] (10), which forces the animal to jump from a perch to one of two platforms placed side by side immediately in front of the perch. If the pigeon jumped to the correct platform it was allowed to remain on it a few seconds in darkness. However, if it jumped to the incorrect platform the latter fell and the pigeon was dumped to a canvas net placed about a meter below.

The jumping perch was 2.5 × 13 cm in size. The landing platforms measured 13 × 18 cm, and were separated by 9 cm. The distance between perch and platforms was varied systematically, as described below. The perch was covered with a corrugated piece of rubber hose to provide better footing for the animal, and on either end were round aluminum discs to prevent the bird from falling off to the side. The platforms were covered with felt to assist the bird in landing.

A locking device, which was operated from outside the apparatus, allowed one or both of the platforms to be locked. Both platforms were locked during training, but

[4] It was at Dr. Yacorzynski's suggestion that this apparatus was used for testing visual acuity. The writer is greatly indebted to Dr. Yacorzynski for permission to see the apparatus and to borrow plans before a description was published.

during the tests one platform was unlocked. Immediately behind the platforms was a large plate of glass. It was painted black except for a 10 cm square window behind each platform through which the pigeons viewed the stimulus objects.

To exclude extraneous light the perch and platforms were enclosed in a large box painted black on the inside. Along one side were black curtains to allow the experimenter easy access to the inside of the box, and one-way vision windows to permit easy observation.

Immediately behind the plate glass windows at the back of the landing platforms was the stimulus-plate holder. The stimuli were alternated by a simple movement of this plate. The holder was mounted on a separate table so that the distance from the stimuli to the windows could be varied.

Behind each stimulus was a plate of flashed opal glass. The stimuli were illuminated from behind by a lantern-slide projector with a 200 watt light. The lines of one stimulus were horizontal; those of the other stimulus were vertical.

In the apparatus used by Halstead and Yacorzynski (10) a quantitative index of obstruction or motivation was obtained by placing the bird on a perch, whose rate of rotation could be increased in steps until the bird either jumped to one of the platforms or fell. Their procedure, however, was found to be unsatisfactory in this experiment, except at small jumping distances of less than 30 to 40 cm, since the birds would stay on the perch until they fell, and did not readily learn to jump to the platforms. They were also hard to train unless the distances were made small. The motor-driven perch was therefore discarded and replaced by hand motivation as described below.

Accurate lines 1 mm and ½ mm in width on cards 12 inches square were made with a fine drawing pen fastened to the screw-threading mechanism of a precision lathe. These master copies were either reduced or enlarged photographically on 8 × 10 inch Process plates to get a series of 11 stimulus plates with lines of different widths. The narrowest lines were 0.015 cm; the widest 0.3 cm. The size of the steps between members of the series varied within the limits of 20 to 50 percent increase.

The lines were a dense black; the spaces clear glass. When the plates were placed in the stimulus holder and illuminated as described above, they appeared as a series of dense black lines separated by white spaces of equal widths.[5]

To prevent flight the wings of the birds were taped behind the back before training until they were well-tamed. It was found that after the pigeons had been trained to jump without using their wings they did not use them when free except for balancing when landing on the platforms.

The birds were trained to jump to the platforms by first placing them on the hand of the experimenter about 3 inches from one of the platforms. They hopped to the platforms readily. The distance was gradually increased until the birds were jumping from the perch to the locked platforms. Finally, the platform under the negative stimulus was unlocked, and the pigeon then readily learned to avoid this stimulus, and to jump to the positive stimulus.

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[5] These stimuli had several advantages over those used in most animal work in previous experiments. First, they provided uniform lines without fuzziness or irregularity at the edges and the contrast was very high. Second, the use of photographic reductions permitted finer lines than could be obtained with accuracy from architect's drawings, and there was no chance for irregularities due to shrinkage such as is found in photostat copies of such drawings. Third, they were relatively cheap as compared with costly engravings which are necessary to obtain lines and spaces of comparable uniformity, contrast, and accuracy.

Experimental observations were made at night. The jumping box was always kept dark except during the time the birds compared stimuli and jumped. This was done principally to facilitate handling since the birds tended to struggle and tried to escape when picked up in the light.

After the pigeon was on the perch it was touched lightly at the base of the tail to make it jump. In the event that the bird made a correct response it was allowed to remain a moment on the platform in the darkness, and was then returned for another trial. If an incorrect choice was made the bird fell to the canvas net, the lights were snapped off, and the bird was picked up and returned immediately to the perch for another trial.

In order to be sure that no handling cues were unintentionally provided by the experimenter, special tests were introduced in which the writer was assisted by another person who changed the stimuli in such a manner that the experimenter had no knowledge of the correct response. The experimenter motivated the birds as usual. When this was done there was no significant change in scores, thus showing that handling cues were not operating.

The thresholds were arrived at in the following manner. Preliminary training was begun on an easy discrimination. Actual learning of the discrimination usually took about 100 trials. As soon as the bird made a score of 16 correct responses in 20 trials (80 percent) the next smaller stimulus was substituted, and so on until the pigeon broke down. Usually twenty to forty trials were given each night. The scores usually improved rapidly as training continued. Finally a limit of training was reached beyond which improvement seemed impossible. When it was thought the bird had reached such a limit, a 'test' was run which consisted of giving the birds 10 or 20 trials on a fairly easy stimulus and continuing with more difficult stimuli until the bird finally broke down and gave chance scores. Four or more stimuli were always used in such a test series, and the complete series was always given at one experimental session. The birds were run through the complete test series on successive evenings until they had a total of at least 50 trials at each test stimulus. The results of all test series were then averaged to give the results shown in the curves of the next section (Figs. 1–7). The birds were retrained and tested again at each of a number of accommodation distances.

The procedure outlined above was first applied at accommodation distances of 30, 40, and 60 cm. In this series of tests the jumping distance increased with accommodation distance. Illumination, as measured by a Weston Photronic light meter at the stimuli, was 3.1 foot candles. A second series of tests followed which duplicated the above tests at 30 and 40 cm, but which also contained tests at 60 and 100 cm accommodation distance in which the jumping distance was kept at 40 cm. In the second series the retinal intensity of illumination and total retinal area of the stimuli were kept constant, except at 100 cm where total area was reduced to 25 percent and intensity to 77 percent of the original. At 100 cm it was necessary, also, to add a 2.5 volt lamp directly above the platforms to illuminate them during jumping. The light was shaded from the eye of the animal.

An attempt was made in a third part of the experiment to test the acuity under conditions of relaxed accommodation. Tubes were made of wall-board (20.5 cm square, and 415 cm long) and were set at the windows behind the platforms. Photostat paper copies of architect's drawings were used as stimulus objects and these were placed at the extreme ends of the tubes, 415 cm from the ends of the platforms. Each stimulus was illuminated by four 40 watt Lumiline lamps in reflectors. To illuminate

the platforms one shaded 40 watt Lumiline light was placed inside the jumping box above the platforms. The stimuli did not fill the windows, and the sides of the tubes were visible.

The birds showed evidence of discrimination but were variable in response. On some days the birds were as high as 80 percent correct while on others they gave chance responses or developed position habits.

Numerous modifications of this apparatus failed to improve the behavior. It is probable that the apparent separation between the stimuli and the platforms so complicated the problem for the birds that they were unable to react consistently. Therefor the detailed results of this series are not reported.

At the beginning of the first series of tests seven birds, 6 Homing and 1 Tumbler pigeons, were used. As the experiment progressed it was believed that some of these birds were too emotional and they were dropped from the experiment. Two birds died in the course of the experiment. Two new birds were therefore added for the test at 60 cm in the first series. Results are given for all the birds used.

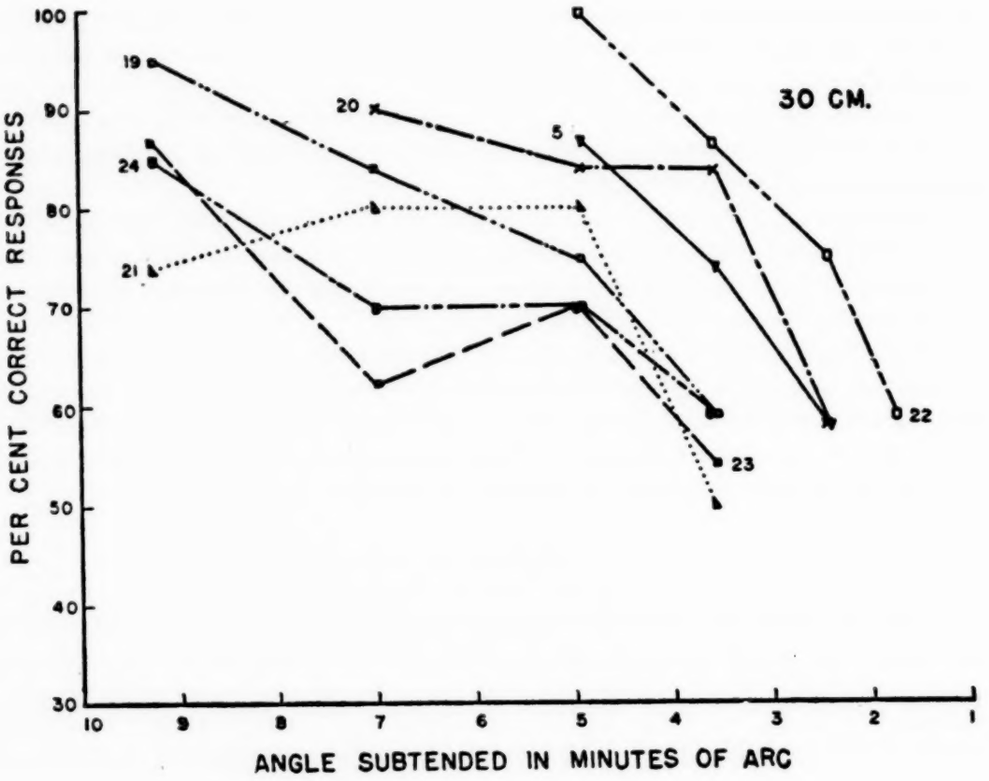
Results

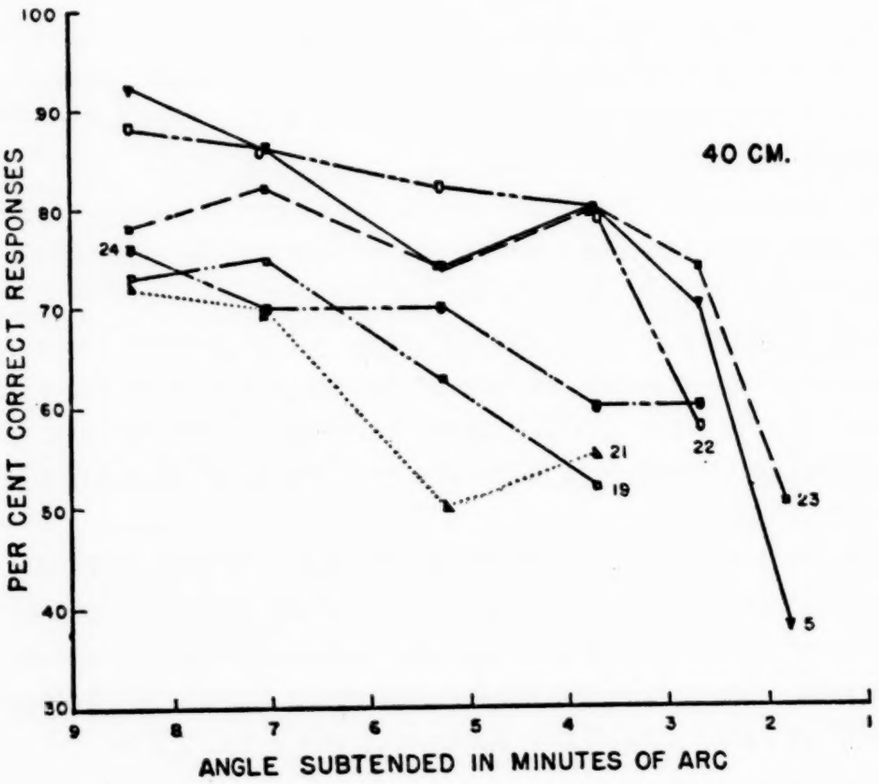
The results of the first series of tests, in which jumping distance as well as accommodation distance was varied, are shown in Figs. 1–3. Figure 1 shows the results for seven birds tested at 30 cm.[6] The visual angle subtended is plotted in minutes of arc on the abscissa, and the percent of correct responses on the ordinate. The numbers on the various curves identify the birds used. If 70 percent of correct responses is considered as indicating a threshold, three birds exhibit a threshold between 3.3 and 2.2 min., and four birds a higher threshold—between 4.5 and 4.9 min. The latter group appeared to be much more excitable than the former.

Figure 2 shows the curves for 40 cm. The curves at this distance are much like those for 30 cm except for a more marked separation of the two groups. The poorer birds never obtained a score much above 70 to 80 percent at any visual angle. They were given extra training of 100 to 200 trials before being tested, but with the exception of bird number 23 failed to improve.

Figure 3 shows the results at 60 cm. There is much less variability here than with the other curves, since the emotional birds were not used, but even the better birds show a higher threshold. In addition, bird number 22 began to show great variability, and could not complete the test. The curve for

[6] The first point on each curve, at 9.2 min, is based on an average of 20 trials. The remainder are based on the usual 50 trials.


30 CM.
PER CENT CORRECT RESPONSES
ANGLE SUBTENDED IN MINUTES OF ARC
19
20
5
24
21
22
23


40 CM.
PER CENT CORRECT RESPONSES
ANGLE SUBTENDED IN MINUTES OF ARC
24
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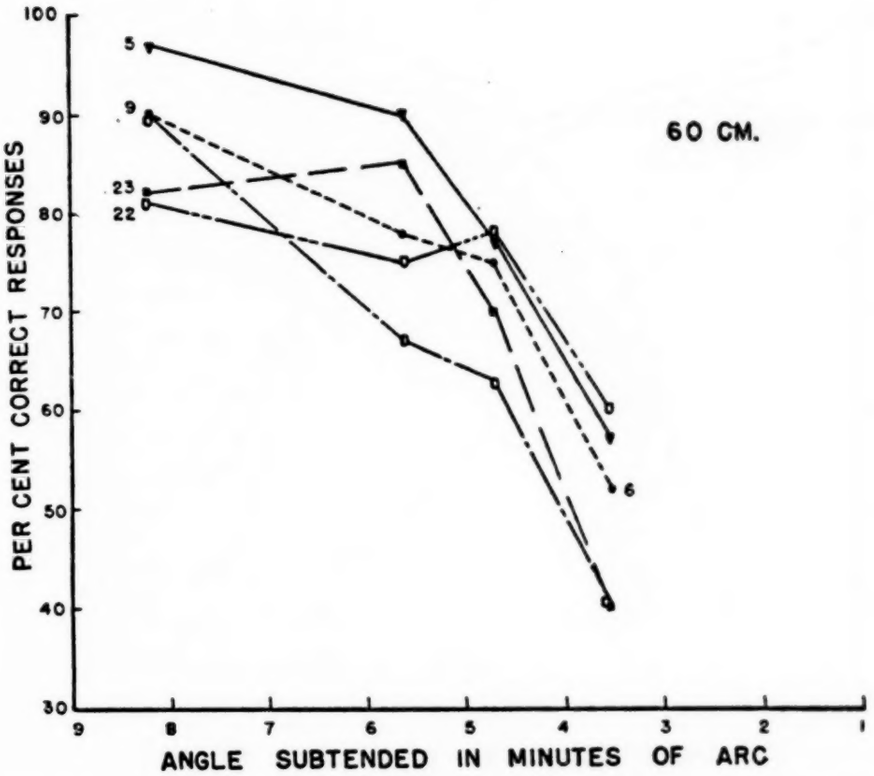
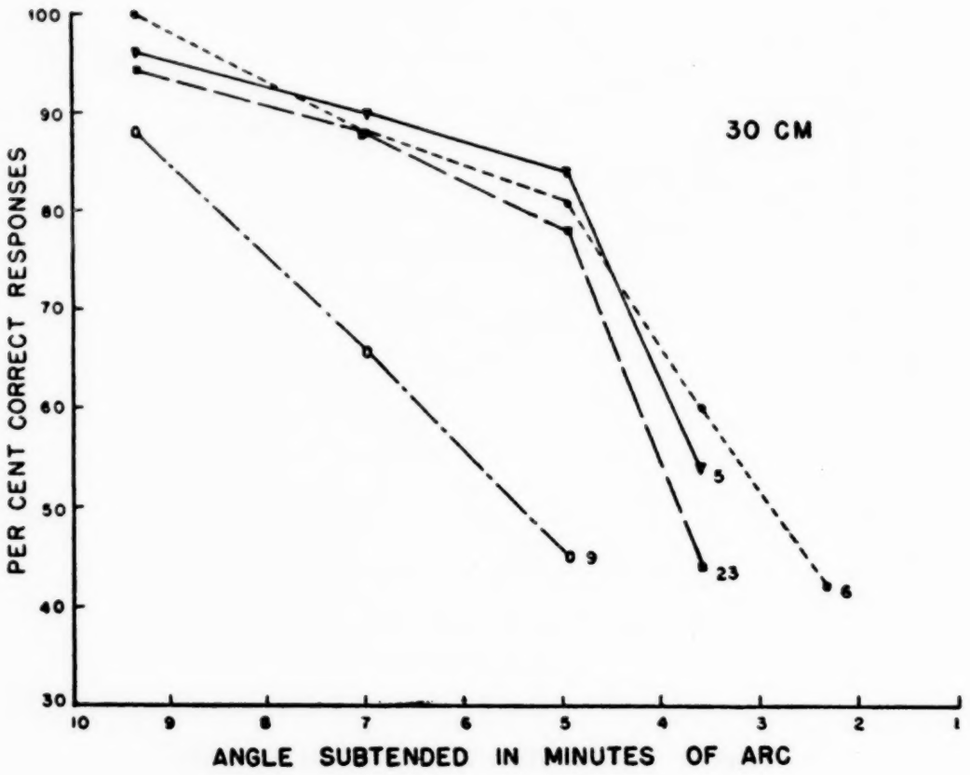


FIGS. 1–3. Response curves for distances of 30, 40, and 60 cm in the first series of tests. The numbers on the various curves designate different animals.

this bird is based on an average of training trials, and the test trials that were completed. The probable reason for the poorer results of all the birds, and the greater emotionality of bird number 22, was the increased distance of jumping as well as the disturbing effects of falling.

The thresholds of the birds are between 4 and 5 min. with the exception of that of bird number 9. The threshold for this bird is around 6 min. The higher threshold, as far as could be determined, was not due to variability or excitement on the part of this animal. This bird happened to be one of the most stable in the group.

To be quite sure that the threshold figures were true measures the birds were retested at every distance. It was considered that the 30 and 40 cm tests with the emotional animals might have given higher than normal thresholds, and that the higher threshold at 60 cm was a function of the greater jumping distance. The results of the second series, which was devised to control this factor and to check the results of the first series, are shown in Figs. 4–7.


30 CM
PER CENT CORRECT RESPONSES
ANGLE SUBTENDED IN MINUTES OF ARC
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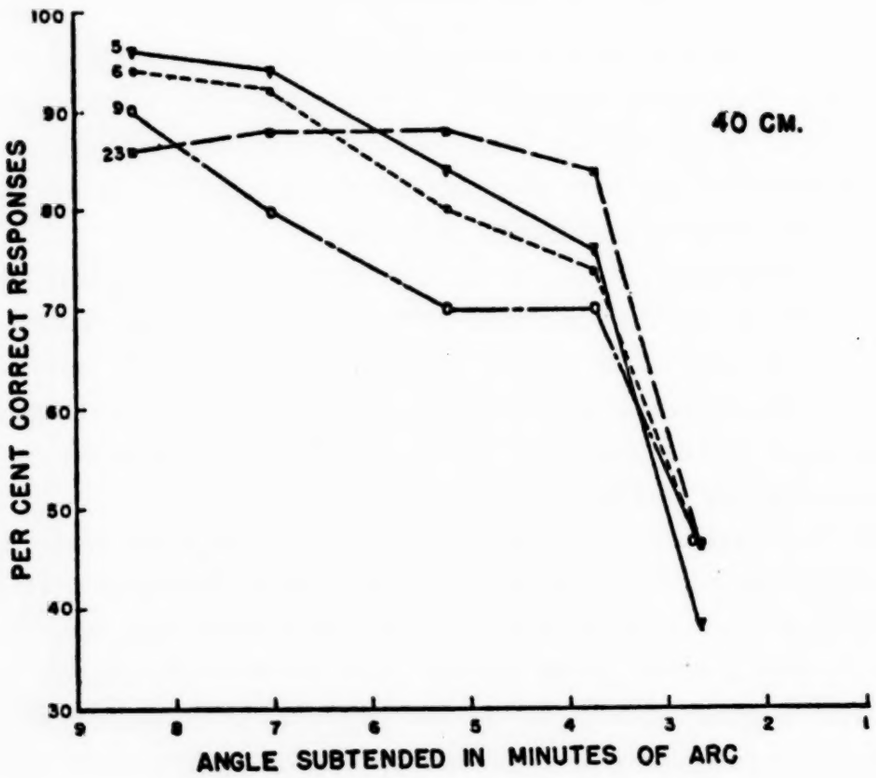
40 CM.
PER CENT CORRECT RESPONSES
ANGLE SUBTENDED IN MINUTES OF ARC
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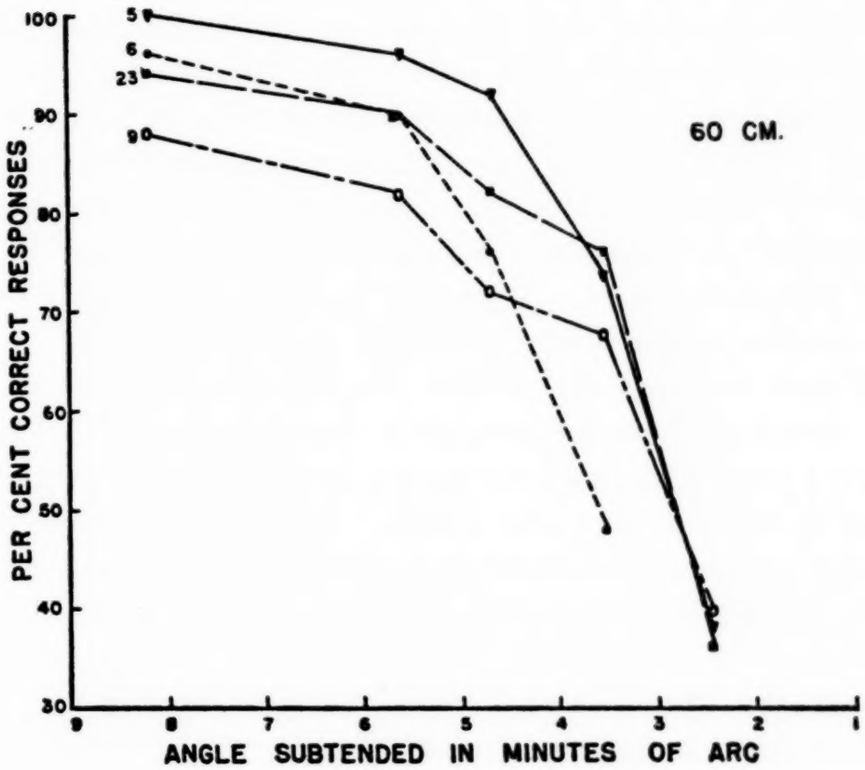

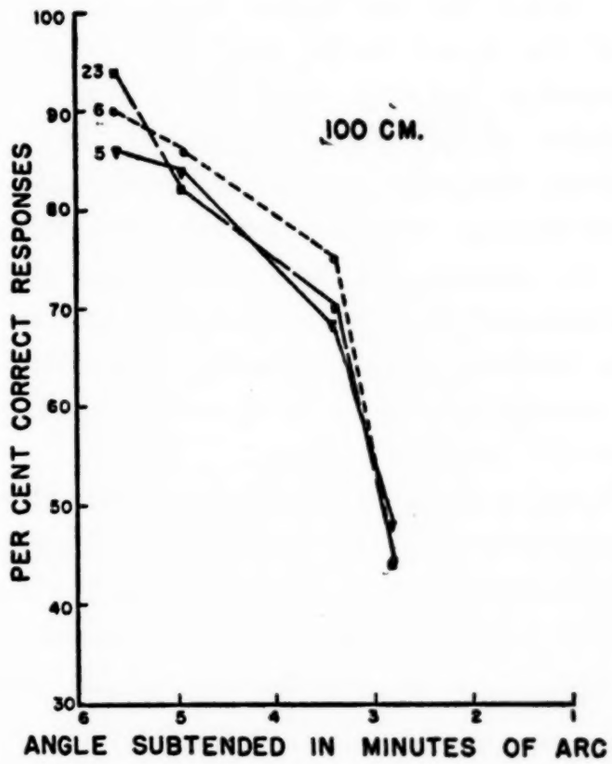

FIGS. 4–7. Response curves for distances of 30, 40, 60, and 100 cm in the second series of tests. The numbers on the various curves designate different animals.

Figures 4 and 5 show the results for four birds at 30 and 40 cm respectively. The curves for the three better birds show somewhat poorer performance in this than in the first series. The thresholds for animal number 9 remain higher than the thresholds for the other animals. There was no indication of emotional disturbance or distraction in this bird during the tests. Therefore it appears that this pigeon was inferior to the others in ability to resolve detail.

Figure 6 shows the results for the four birds at 60 cm. The threshold here for two birds (numbers 9 and 23) is between 4 and 5 min.; and the thresholds for the others (numbers 5 and 6) is between 3 and 4 min. The discrepancy between number 9 and the others is not so obvious here, but inspection of the figure shows this bird to be consistently below the others except near the threshold. It is interesting that in these tests moving the stimuli away from the ends of the platforms produced no change in the performance of the birds and no observable disturbance of behavior.

Figure 7 shows the curves for three pigeons at 100 cm.[7] Inspection of the figure shows that the three thresholds are very close together, between 3 and 4 min. of arc. Observation of the behavior of the birds suggested that this distance represents about the most that the stimuli could be separated from the platforms without undue complication of the problem for the pigeon. It was exceedingly difficult for the birds to discriminate at this distance as judged by the amount of hesitation, looking, and comparing that went on. Nevertheless the acuity shown is as good as that at the other distances.

Figures 8 and 9 show the variation of the threshold value with accommodation distance. The visual angle subtended at the threshold is plotted on the ordinate; the discrimination distance on the abscissa. For the first series (Fig. 8), the threshold is high at 30 cm, decreases at 40 cm, and rises again at 60 cm.

[7] Bird number 9 died during the interval between the 60 and 100 cm test of the second series.

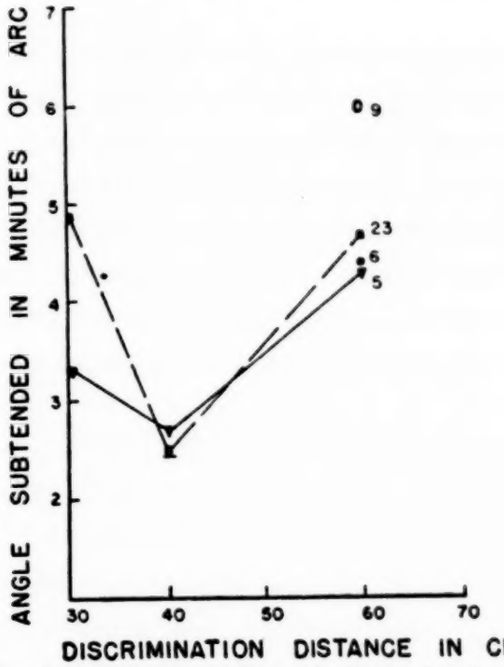

FIG. 8. Relation between threshold and discrimination distance in the first series of tests when distance of jumping was increased from 30 to 60 cm with the discrimination distance. At each point the distance the bird was required to jump was equal to the discrimination distance. The numbers on the various curves designate different animals.

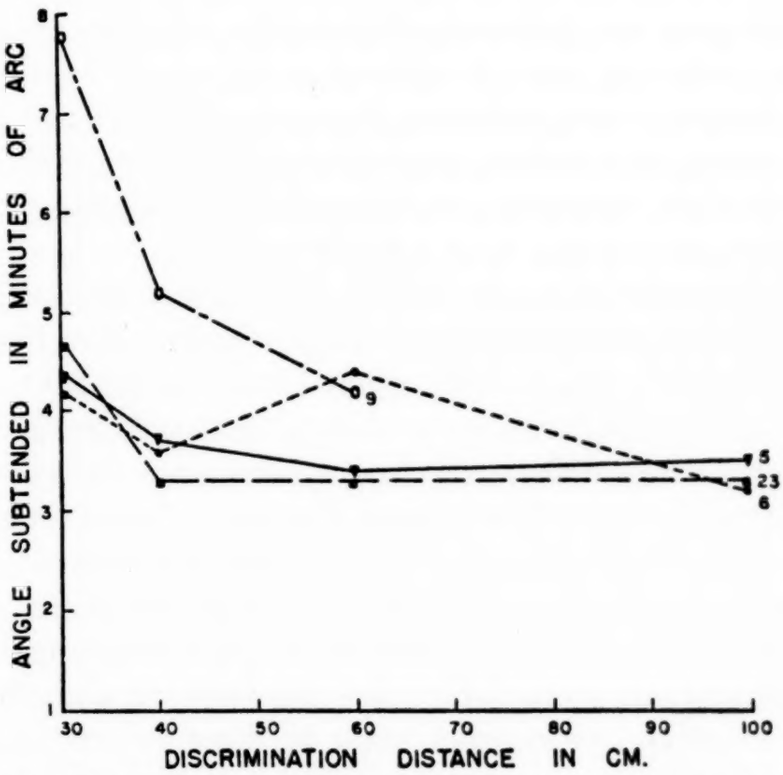

FIG. 9. Relation between threshold and discrimination distance in the second series of tests when the distance of jumping was kept at 40 cm or less for all discrimination distances. At 30 cm discrimination distance the jumping distance was 30 cm; at 40, 60, and 100 cm discrimination distances the jumping distance was 40 cm. The numbers on the various curves designate different animals.

In Fig. 9 are the results of the second series with the jumping distance controlled. There is very little difference in acuity at the accommodation distances shown. It is evident that acuity begins to decrease somewhere between 60 and 30 cm, but the differences between the various distances are not great in relation to the error of measurement of the method. Nevertheless, it seems likely that the near-point of accommodation has been approached or even passed at 40 cm.

Discussion of Results

The results of the present experiment tend, in general, to agree with those obtained by Hamilton and Goldstein (**12**). Both experiments show that acuity is less at an accommodation distance of 30 cm than at the greater accommodation distances of 40 cm and above. However, the thresholds obtained in the present experiment are, in general, somewhat higher at every distance than those obtained by Hamilton and Goldstein. The thresholds obtained by the latter are based on the performance of only one bird, tested on one day. The bird gave the following thresholds: 2.7 min. at 107 cm, 2.8 min. at 66 cm, and 3.8 min. at 31 cm.

In the present experiment it was found that the pigeons varied among themselves, and also there was variation when the same birds were later tested at the same distances. The range of variation was from 2.7–7.8 min.

It is doubtful that any definite conclusion concerning the role of accommodation in acuity can be drawn from Hamilton and Goldstein's results, and even from the present experiments, since the differences at various distances are not much greater than the differences found between successive tests at the same distances in the same pigeons. Nevertheless, the fact that all the birds used in the present experiment tended to show poorer acuity at 30 cm than at 40 cm or 60 cm suggests that the conclusion of Hamilton and Goldstein that the near-point of accommodation lies between 30 and 60 cm is valid. However, more work must be done before the actual relations between accommodative force and acuity are clear-cut.

The thresholds obtained in the present experiment are high compared with the thresholds obtained by Gundlach (7) for two out of three pigeons (0.38 and 0.5 min.). Gundlach used a modified Yerkes-Watson type of apparatus consisting of a central starting-box from which radiated two cloth-covered tubes in the shape of a Y. The stimulus objects were placed at the ends of these tubes, and were 20 feet from the choice point.

It is possible that the divergence of results was due to the different type of apparatus. Since the stimuli were 20 feet from the animal, relaxed accommodation was assured. However, it seems unlikely that this factor was of primary importance since the results of the present experiment and also those of Hamilton and Goldstein tend to show that acuity is constant above 40 or 60 cm.

Gundlach reports great difficulty in training the birds. There was no chance to start with fairly large lines and spaces and gradually substitute smaller ones until the pigeon broke down as had been done previously in problems of this type. The pigeons never performed well enough to give clear-cut evidence of having learned the problem on any stimulus. Gundlach states, "It seemed that the birds would almost solve the problem, but then fall back into some position habit, or some other basis of choice that was entirely unpredictable" (7, p. 333).

His method was to train the birds on wide lines until there was general orientation to the problem. He then successively presented them with finer and finer lines giving about 50 trials at each new step until the animals had been presented with the smallest sized lines. Then the whole series was repeated. This was done several times. Naturally, when position habits appeared the birds were forced on the wrong side to break the habit. This piling-up of errors served to vitiate any evidence of a learning curve. At no time did the birds achieve a criterion of learning such as is customarily used, say 90 percent correct responses in 20 trials.

It is likely that the difference between Gundlach's results and ours is due to the differences in the statistical methods

used in the calculation of thresholds. Gundlach selected series of runs in which the influence of position habits seemed to be slight and attempted to calculate the chances that these series showed significant evidence of discrimination. In the present experiment all runs of the test series are included in the calculations. In one part of the present experiment tubes similar to those used by Gundlach were tried (see p. 596). The pigeon showed the same behavior as reported by Gundlach for his animals, *i.e.*, they might show evidence of discrimination on one day, and on the next day form position habits to give a chance score. Had these pigeons been run a sufficient number of trials and the data treated by Gundlach's methods there is no doubt, in the opinion of the writer, that results similar to those of Gundlach would have been obtained. It was decided, however, to use data only where the animal gave *consistent* evidence of discrimination when tested from day to day.

There is also another possible reason for the divergent results. In the present experiment the more severe type of punishment may have caused the animals to break down sooner than if a less severe type had been used. However, observation of the behavior of the animals leads the writer to believe that this factor was not of primary importance. The birds at no time gave the impression of not trying when the jump was moderate, but gave evidence of not being able to *see* the lines when they were made fine, such as hesitation before jumping, and comparing of stimuli by looking first at one and then the other. Such behavior was not present when the lines were wide and easily discriminable.

Summary

In an experiment designed to measure minimum separable acuity of pigeons under various conditions of accommodation it was found that acuity is poorer at 30 cm than at greater distances. Results obtained from four birds tested at various accommodation distances gave the following results when jumping distance was kept at 40 cm or less: 30 cm, 3.3–7.8 min; 40 cm, 2.7–5.2 min; 60 cm, 3.3–4.2 min; 100 cm, 3.2–

3.5 min. Increase in jumping distance tends to produce an increase in threshold. Differences in acuity thresholds at various accommodation distances are not great in relation to individual differences and chance errors. Nevertheless, it seems likely that the near-point of accommodation has been approached or even passed at 40 cm.

(Manuscript received November 30, 1938)

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FINGER OSCILLATIONS AS INDICES OF EMOTION. II: FURTHER VALIDATION AND USE IN DETECTING DECEPTION

BY F. K. BERRIEN

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In a previous paper the digitalgraphic technique and apparatus have been described.[1] That paper also presented a method of analyzing the finger oscillations which resulted in a composite index. Marked deviations of that index from the experimentally determined normal for a given subject were shown to be indicative of emotion in mental hospital patients. The present experiment was designed as a further effort to gain evidence of the validity of the procedures developed previously.

The attempt has been made to establish, under laboratory control, situations of a rather mild emotional nature. During this experiment, emphasis has been placed upon detecting deception but the effect of emotions other than the concomitants of deception has also been examined.

Briefly, the aim of this series of observations was to test the utility of the digitalgraph and the composite index when applied as a research tool or as a means of determining guilt or innocence is a given individual.

Procedure and Subjects

The subjects for this experiment were 12 male college students, 9 of whom were undergraduates recruited from the introductory course in psychology. The remaining 3 were graduate students in the department.

The first three subjects that were examined followed a slightly different procedure than those who succeeded them. When they first entered the experimental room they were given an opportunity to draw two cards from a deck of playing cards. They were instructed to remember which card they drew first and which they drew second.

[1] F. K. Berrien, Finger oscillations as indices of emotion. I: Preliminary validation, *J. Exper. Psychol.*, 1938, 24, 485–498.

The cards were stacked in such a manner that the experimenter knew the card drawn in each case almost as soon as the subject, but the latter was not aware of this fact.

General instructions were the same as in the previous experiment. Essentially, the subject was required to flex his index and middle fingers at each signal from a metronome, which was set for sixty beats per minute. The movements were recorded by appropriate apparatus on a polygraph tape. After the subject had attained an even rhythmical movement, questioning was begun. The first three subjects were informed in advance that they would be questioned about the cards they had drawn. In reply they should attempt to deceive the experimenter. These questions were framed so that the answers could be merely a simple 'yes' or 'no.'

Since all the subjects reported little excitement in response to such card questions even when they falsified, questions were substituted pertaining to a more complicated and exciting situation. Aside from this change which applies to questions 8 to 11 and 25 to 28, the rest of the procedure was the same for all 12 subjects. The revised procedure was as follows:

Two sets of directions were formulated, each sealed in a separate envelope. The subject was told to take the envelopes to a nearby room, open only one, and follow the enclosed directions.

The envelopes contained the following directions:

> Go to the window and count as many telephone poles as you can see. Remember the number. While sitting on the work bench draw a picture of a knife on the enclosed slip of paper. Put the paper in your pocket. Now return to the experimental room (A—1).
>
> Estimate the height of the electric light fixture above the floor. Stand on a chair and write your name backwards on the enclosed slip of paper. If your name is Harry you should write Yrrah. Put the slip of paper in your pocket. Return to the experimental room (A—2).

The preliminary instructions given the subjects were as follows:

> Here are two envelopes which contain directions for performing certain acts. I want you to take them both down the hall to the shop and open only one. Follow the directions exactly and then return here. I will then question you about the things you did and I want you to deceive me if possible. Try to fool me by your answers concerning the things you did.
>
> Now the questions are of three kinds. First are those which will refer to acts or events that will have occurred no matter which set of directions you follow. You will recognize these questions readily. It is of course to your advantage to answer these questions truthfully since they will not reveal which set of directions you followed. The second kind of question pertains to acts and events that are duplicated in the two sets of directions but which you have no way of knowing are duplicated. If these questions are answered truthfully they will not reveal which set of directions you followed. The third kind refers to acts and events that are specific for one set of directions or the other. These are the ones which if answered falsely will confuse me or deceive me into believing you followed the directions which you did not. Now the catch is this. You have no way of distinguishing between the last two kinds of questions. All you know is that on some questions you can safely tell the truth without fear of detection. If you lie to questions that concern events that are duplicated in the two sets you are giving yourself away; that is, your alibi does not conform with the acts I know you must have performed. On the other hand if you tell the truth on the questions which are specific for one set or the other, you are then telling me too much, for I then know which set you followed.
>
> You see, this is similar to the situation where the police are questioning a suspect. The reason the man is a suspect in the first place is because the police have some information that connects the suspect with the crime. Now the suspect may know the police possess some information against him. If he lies

about the information they will know immediately that he is lying. There may be other information that the police possess or may later acquire concerning the suspect's activities. As long as this information does not connect him directly with the crime, it is of course to the advantage of the suspect to admit the truth of such information. The difficulty is that the suspect may not know exactly how much can be safely admitted since he does not know how much the police may have against him. Now then, the principal reason for questioning the suspect is to collect additional information or to confuse the alibi. The suspect has done something which the police do not know about. He can lie about these acts and run a good risk of not being caught. A good alibi in this case as in the experiment consists of telling the truth about the things that are known about your activities and lying about the things which are not definitely known. Now if you establish a consistent alibi you get a quarter. If you get caught in your lies I keep the quarter.

Upon the subject's return he was given these additional instructions:

During the course of the next few minutes I am going to ask you to do some mental arithmetic. You are to get the answer as quickly as possible. If you take too long to solve the problem this fuse will blow in your face, like this (demonstrate). If some of these sparks should fall on your arm they might give you a slight burn. Once you give me an answer don't correct it. If it is wrong the fuse *may* blow about 10 or 15 seconds after you give the answer. You see, the fuse may blow any time after I dictate a problem except when you get the correct answer quickly. If you don't understand the problem ask to have it repeated. Any questions?

Now, all I want you to do is to keep time with the metronome by moving your fingers clamped to this lever. Each time the metronome ticks press down. You will have about two minutes practice to get used to the rhythm. The movements will become very automatic and almost unconscious. Make them as smooth as possible. No matter what happens keep tapping in time with the metronome. It is not necessary to press the key as far as it will go. The least movement will record. Do not lift the fingers higher than this (demonstrate), and do not hit 'bottom' like this (demonstrate). Nothing will happen if you should move your fingers to these limits but I would rather you would not.

The digitalgraph was then started. After an even rhythm had been established the following questions were asked. An interval of 30 or 40 cycles was permitted between each verbal response and the succeeding question.

1. Is today (Sunday)?
2. Did you have breakfast this morning?
3. What answer do you get when you add 256 and 372?
4. What answer do you get when you subtract 31 from 72?
5. What answer do you get when you subtract 221 from 435?
6. What answer do you get when you add 68 and 12?
7. Is the weather clear today?
8. Did you carry two envelopes out of the room a moment ago?
9. Do you carry a special slip of paper in your pocket now?
10. Did you try to count telephone poles while in the shop?
11. Did you just write your name backwards?
12. Is this the Hare Laboratory?
13. Look at this picture and remember what I say about it. (Read short account of case illustrated.[2])

[2] For example, while the subject looked at a hand covered with gangrene scabs in natural color he was told, "This patient was 43 years of age. From around the edges of the greenish blue scabs oozed a pus which gave off a nauseating odor. From time to time the patient would pick the scabs with her teeth and suck the pus from the sores."

14. Is your name John?
15. Look at this picture and remember what I say about it.
16. Do you have a headache?

At this point the digitalgraph was stopped and protocols taken. A second pair of envelopes was given the subject with the same preliminary instructions as before. These envelopes contained the following directions:

> Count the number of chairs in the room. Write the number on the enclosed piece of paper. Put the slip in the envelope. Untie and retie your shoestring. Return to the experimental room (B—1).
>
> Count the rungs on one of the chairs in the room. Write the number on a slip of paper enclosed in the envelope. Return the slip to the envelope. Tie a knot in the window shade cord. Return to the experimental room.

The questions for the second part of the experimental session included one additional type. Questions 22 and 23 have been called 'tricks' because regardless of the answers given the subjects were told they were wrong and the fuse blew. The questions for the second half were as follows:

17. Is this the 9th of March?
18. What answer do you get when you add 652 and 372?
19. What answer do you get when you add 45 and 12?
20. What answer do you get when you subtract 14 from 28?
21. What answer do you get when you subtract 112 from 201?
22. Wrong, do it again. Subtract 112 from 201.
23. Wrong, try it again.
    Forget about the problem.
24. Did you have lunch yesterday?
25. Were you in the shop a moment ago?
26. Did you retie your shoe string while in there?
27. Did you write a number on a slip of paper?
28. Did you handle the window shade cord in the shop?
29. Is it now approximately 4 o'clock?
30. Try to remember what I say about this picture.
31. Is this city Philadelphia?
32. Try to remember what I say about this picture.
33. Do you feel tired?

It is apparent that the above procedure includes a variety of situations of a rather mild emotional nature separated at intervals by control questions.

Minor variations occurred in this procedure from time to time as a result of temporary conditions. For example, the last two subjects were not shown the pictures. Four of the subjects lied on control questions which, of course, reduced the number of control responses. Some of the subjects also failed to give correct responses on question 21, necessitating an additional question exactly the same as 23 which was designated 23b.

Results

Quantitative

The finger records of this experiment were analyzed according to the methods described in the previous paper. The composite index was derived by solving the equation $X = 32L + V - 5T$ in which X equals the composite index;

L is the index [3] for length per cycle; *V* is the index for variability of troughs; and *T* is the index for *T* units (a measure of the rapidity with which an extension movement is changed to a flexion movement).

The atypical indices were determined as previously described except that a criterion of 3.5 A.D. units deviation from the control mean was used instead of 4 A.D. units. This change in the criterion was justified since the subjects in the present study were given a greater number of control questions which resulted in a more accurate determination of the normal spread of composite indices.

In Table 1 we have the frequency of atypical indices in-

TABLE 1

Columns headed *a* contain the total number of responses in the category. Columns headed *b* contain the number of responses with composite indices exceeding M of controls + or − 3.5 A.D.'s.

Subject	Ar.		A.F.		T'k.		Tru.		T.G.		Lie		Pic.	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
Cha.....	6		2	1	2		6				2		4	
Stu.....	5		3		1		4				3		4	1
Fin.....	7	1	1		3		4		1		3		4	
Fis.....	5		2		2		2		3	1	2		4	
Jen.....	5	1	1	1	3		1		3	1	6	3	4	
Cro.....	4	1	3	1	2		2		2		4	2	4	2
Hub.....	7	1	1	1	2		2		4		2		4	
Wil.....	5		3		2		2		2		3		4	
Lip.....	6		2	1	2		2		2	1	4		3	1
Sch.....	7				2		3		4		2		4	
Tho.....	6	1	1		3		2		3	1	5	1		
Dia.....	4		3	1	2		2		1		6			
Totals....	67	5	22	6	26	0	32	0	25	4	42	6	39	4
%.....	7		27		0		0		16		14		10	

Legend: Ar. —Correctly solved problems.
A.F.—Incorrectly solved problems followed by fuse.
T'k.—Trick situation (see text for description).
Tru.—Simple truthful responses.
T.G.—Admissions of guilt.
Lie —Falsehoods.
Pic. —Pictures accompanied by description.
R.P.—Response period.

[3] The index for a particular variable is the ratio of the average value obtained in the normal period (ten beats just before a question) to the average value obtained in in the response period (those beats from the moment a question was asked to a point ten beats after the answer was given). For a full description of the analysis see *op. cit.*

dicated by subject for each of the seven types of experimental situations. Examination of the table indicates a T.G. column which the legend indicates as truthful admissions of guilt. These are the responses in which the subject admitted an act which was included in the directions chosen. The simple truth responses are those in which the subject answered truthfully to questions which were not specific for either set of directions (Questions 8 and 25). In contrast with these are the admissions of guilt which in spite of their being truthful also very likely involved an emotional aspect that differed from that found in the simple truthful answers.

The last row of the table contains the percentage of atypical indices in each of the experimental categories. It will be observed that the mental arithmetic problems which were incorrectly solved and followed by the fuse blowing gave a larger percentage of atypical indices than any other. The admissions of guilt and falsehoods have about the same percentage of atypical indices. It is noteworthy that not a single truth response received an atypical index.

Qualitative

In addition to the quantitative measures thus far presented certain other observations were made. These observations were not readily reduced to numbers but were sufficiently clear from an inspection of the records to merit attention. These observations are presented in the form of comments in Table 2.

TABLE 2

Subject	Ques.	Qualitative Observation
Stu.	3 A.F.*	Just before answer was given, responses were small in amplitude, irregular in timing and faster than signals so that 5 oscillations were made to 4 signals.
	18 A.F.	Just after answer was given responses are of the same character as in 3 above.
	23 T'k.	For a period of 30 seconds after blowing of fuse in 22 the finger responses are irregular in amplitude and timing to such an extent that no part can be called a normal period. Hence 23 was not measured. When commanded to forget problem the responses became regular and even.
Dia.	3 A.F.	An extra response inserted in R.P.

	5 A.F.	Responses are slower than signals but regular in timing in R.P.
	9 Lie	Amplitude first decreases markedly in R.P. followed by a return toward normal amplitude.
Fis.	3 A.F.	Not measured for composite index because responses are made at double time with a marked decrease in amplitude.
	5 Ar.	Following sample of R.P. measured, the record shows the same characteristics as in 3 above.
	18 A.F.	Same as 5 above.
	21 Ar.	Not measured because all of R.P. shows decrease in amplitude and responses are faster than signals. Problem was difficult but correct answer was given.
	22 T'k.	Same as 5 above.
Hub.	5 A.F.	During R.P. there is a fairly regular increase in length from beginning to end accompanied by a decrease in T units.
Jen.	23b T'k.	Just following the R.P. there is a marked increase in length. No fuse was blown although subject expected it.
Fin.	5 Ar.	During R.P. the length of cycle varies greatly.
	10 Lie	Beats during R.P. are regular in timing but faster than signals.
	19 Ar.	Same as 10.
	21 Ar.	Same as 10.
	20 Ar.	In middle part of R.P. responses are regular in timing but slightly faster than signals.
	22 T'k.	Same as 10.
Wil.	3 A.F.	During R.P. length progressively decreased.
	5 Ar.	During middle part of R.P. responses were faster than signals but regular in timing.
	22 A.F.	Period following portion of R.P. measured was characterized by very small, irregularly timed responses. Responses did not synchronize with signals.
	26 Lie	Not measured because 3 responses at middle of R.P. reached the upper limit of excursion. Succeeding responses are greater in amplitude than normal period.
Lip.	18 A.F.	Length progressively increased during R.P.
Sch.	3 A.F.	Problem was not completed. During R.P. previous to fuse blowing the finger responses are generally greater in amplitude than normal but exceedingly irregular in timing and extent. Several beats are completely omitted. Subject reported embarrassment and annoyance.
	18 A.F.	Responses during R.P. are somewhat slower than signals but regular in timing. They progressively increase in amplitude up to the moment the answer is given.
	23 T'k.	R.P. responses are faster than signals in middle of period. They are also irregular in timing.

* See Table 1 for key to symbols.

It will be noted that many of the situations referred to in the above table were not measured and therefore do not appear among the quantitative results of the previous section.

The reason for this is obvious. The emotional state may produce such a change in the finger movement that a brief glance reveals that change. The usual quantitative measures are therefore not feasible and are unnecessary from a diagnostic standpoint.

An inspection of the qualitative observations shows that not a single control question, and no truthful responses are included. On the other hand, 8 correctly solved arithmetic problems, 8 incorrectly solved problems, 3 falsehoods and 3 trick situations do show obvious qualitative changes which are either obscured by the composite index or were so apparent that the composite index was not computed. These qualitative changes appear to be as valid indicators of emotional disturbance as the composite index.

Therefore, the cases showing obvious qualitative changes which have not earned atypical indices may be combined with those possessing atypical indices. When the two kinds of data are considered together there is an appreciable increase in the percentage of emotional responses detected through the study of finger oscillations. The following table indicates the total percentage of cases in each category thus revealed.

TABLE 3

PER CENT OF CASES SHOWING QUALITATIVE AND QUANTITATIVE CHANGES

Problems correctly solved	19
Problems incorrectly solved	64
Trick situation	12
Truth	0
Truthful admission of guilt	16
Falsehoods	21
Pictures	10

RELIABILITY OF QUANTITATIVE RESULTS

An attempt was made to gain some notion of the reliability of the data just presented. The question may be asked, Are the observed changes in the index adventitious? Would similar alterations occur in the absence of emotional stimuli? In other words, what would happen to the composite index if the subject merely executed finger oscillations in the

absence of questions or emotional situations of any kind? Five of the subjects included in the main series were later recalled to the laboratory and asked to make additional control records of this sort. They were told to keep time with the metronome as they had done before. They were informed that no questions would be asked. Record was taken for approximately 15 minutes.

From a theoretical standpoint it would perhaps be desirable to have records of the same length as in the regular experimental sitting. As a practical matter of fact three of the subjects reported being bored toward the end of the 15 minute period. Hence it was necessary to avoid the entrance of such vitiating factors by demanding only a comparatively short record which quite adequately sampled the normal performance of the subjects.

In analyzing these records groups of 20 cycles each were picked at random. Each group was divided into two 10 cycle periods, the first of which was treated as if it were a normal period and the second as if it were a response period. Composite indices were derived according to the usual method.

The results of this procedure revealed that the composite indices vary from sample to sample within a given subject's record, but the range is exceedingly restricted. Moreover, the range and central tendency for each subject do not differ significantly from the control indices derived in the main series of the experiment. None of the indices in this supplementary control series showed such great deviations from the mean as were observed in response to emotional situations in the main series.

These data therefore lead to the conclusion that the range of fluctuations in the composite index on the control questions of the main series is of a chance order and may be expected even when the subject is not presented with questions or emotional situations. In the light of this finding, the marked deviations take on added importance.

Discussion of Results

The percentage of emotional situations detected by the composite index is admittedly small but sufficiently great to demonstrate that finger movements manifest characteristic changes when the individual is confronted with an emotion-provoking situation.

The results in Table 1 are of interest in the light of the analysis presented in another paper [4] which points out the similarity between the lying situation and mental arithmetic done under pressure of time with a penalty for incorrect solutions. The subjects invariably reported greater affective disturbance in response to the mental arithmetic than to the lying situations, which is in harmony with the objective data. According to the analysis suggested in the last reference we concluded that problems correctly solved would involve little change in affective tone and would be similar in this respect to truthful answers to questions. On the other hand, incorrectly solved problems would precipitate affective responses similar to those accompanying deception. The data in Table 1 are in general agreement with these assumptions since 7 percent of the correctly solved problems and 27 percent of the incorrectly solved problems had atypical indices. This relationship is similar to that existing between truthful responses and falsehoods.

It may be of interest to point out the manner in which falsehoods were discovered on certain control questions. In the case of subjects Jen., Hub., Tho., and Dia. the routine computation of the control indices showed one or more 'control responses' in each record which were markedly different from the rest. Subsequent questioning of these subjects revealed that on 5 of the 6 suspected questions the subjects had lied. Only 3 of the 5 falsehoods thus discovered met the criterion of significance, which may indicate that the criterion adopted is somewhat higher than necessary.

A consideration of the qualitative results leads to the belief that whereas the composite index alone may be of some value

[4] Berrien, F. K., A note on laboratory studies of deception, *J. Exper. Psychol.*, 1938, 24, 542–546.

in detecting emotional disturbances, qualitative changes not affecting the index are of importance. Indeed it is quite possible that in some cases the composite index will be of less importance than qualitative judgments of the regularity of timing, omission or addition of oscillations, irregularity of amplitude and similar characteristics which are readily discernible without resort to the time consuming and laborious measurements required for the composite index. The protocols tend to indicate greatest affective disturbance when the qualitative changes were quite obvious. It may be, therefore, that the composite index will prove of value in detecting moderately intense emotions while a qualitative evaluation will suffice where more intense emotions are being studied.

With respect to the possible use of the present technique in actual crime detection work, it appears obvious that it can be of little value if used alone. The data indicate that with some subjects it may be possible to detect with certainty approximately 50 percent of the falsehoods (See Table 1, subjects Jen. and Cro.). In other subjects the technique may not reveal any lies at all. In spite of this limitation the technique should be of some value if it is employed along with other indicators of emotional disturbance.

Summary and Conclusions

A method of analyzing finger movement records for their indices of emotion was developed with psychotic patients as subjects. This procedure which culminates in a composite index was applied then to similar records made by normal university students. The records of the second experiment verified those of the first in that atypical composite indices occurred only in situations of an emotional character. Mental arithmetic problems done under pressure of time with a penalty for incorrect solutions were more frequently accompanied by atypical indices than any other type of situation presented to the subjects. Truthful answers to questions concerning the previous activity of the subjects were never accompanied by atypical finger movements. In two subjects, half of their falsehoods were accompanied by atypical altera-

tions in the finger movements. For the 12 subjects only 14 percent of the falsehoods had atypical composite indices. The fluctuations in the composite index accompanying control questions are comparable to changes which appear in the absence of questions of any sort.

On the basis of the discussion and results which have been presented, the conclusion drawn from the previous study remains justified; namely, that the existence of an atypical composite index is evidence of emotion, but the absence of an atypical index does not necessarily indicate the absence of emotion.

Qualitative evidence has been presented which indicates that changes in finger oscillations not revealed by the composite index occur in response to emotional situations. If the quantitative and qualitative data be combined, 64 percent of the incorrectly solved problems and 21 percent of the falsehoods give evidence of emotional responses through finger movements. The digitalgraph technique is not recommended as a substitute for, but rather as a supplement to other indicators of emotion.

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THE DISTRIBUTION OF MUSCULAR ACTION POTENTIALS DURING MAZE LEARNING *

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To any investigator interested in the relationship of neuromuscular changes concomitant with psychological processes at least two possible methods of approach are open. One can, on the one hand, direct the subject in these muscular changes and measure the consequent effect upon the psychological processes, and on the other hand one may direct the behavioral activity of the subject and note the changes occurring in the muscular system. The two methods are obviously closely interrelated.

Of the two approaches, the former has enjoyed the greatest popularity, largely because of the technical difficulties involved in the measurement of muscular tensions. Of those relatively few studies which do obtain some indication of tensions during laboratory controlled behavior, only three or four throw any light on the problem of tensions during motor learning.

Ghisselli (**5**) showed that tensions decrease markedly in trials following mastery of a visuo-motor task when speed is not a factor. Stroud (**7**) found that the subjects' tensions decreased during the learning of a difficult maze, but increased during the learning of a comparatively easy maze. Freeman (**4**) observed a progressive isolation of tensions in the body member performing a learning task. In addition, Bills (**1**) noted that the tension of arm and jaw muscles increases when a subject is running the more difficult parts of a finger maze.

Problem.—As a theoretical frame into which to place the problem for further investigation, the peripheral motor theory discussed by Davis (**2**) best fits the present research.

* Graduate research under the direction of R. C. Davis. The writer is indebted to him for guidance and the use of equipment.

This theory maintains that any changes found in tensional patterns must be intimately related to those psychological processes so controlled. To accept this theory finally we must satisfy ourselves that there is, according to Davis, "an occurrence of different patterns of muscular activity for different psychological processes, and, conversely, of the same motor pattern (to some accepted degree) for the same psychological process on all occasions" (**2**, 5f).

The case for learning in a peripheral theory lacks evidence, certainly, and what little there is seems to be confusing. Tensions are found to increase in one case and decrease in another; they are found to decrease during mastery, especially in non-performing body parts; they are found to increase during difficulty in performance. Questions following these facts lead directly to the problem at hand. Can one establish a progressive tensional pattern through a learning process and relate it to a specific behavior pattern? The problem is to attempt to demonstrate the differential tensional pattern concomitant with learning by means of measurements of the distribution of action currents during the learning process.

Method.—Perhaps one should not be too confused by the results of studies previously mentioned, because their methods of measurement were comparatively crude. Since the development of the cathode ray oscillograph, the action current technique for determining the level of tension has come into most general acceptance. Equipment of this sort permits undistorted recordings of electromyograms at extremely high sensitivity. In the Indiana University laboratory the apparatus in use consists of surface contact electrodes picking up the electrical discharge from the muscle beneath. Feeding through a high gain, condenser coupled amplifier, the action current is impressed upon the cathode ray tube where it may be observed as a bright spot of light in rapid oscillations. These deflections become permanent records when photographed by the high speed, moving film camera, and later measurements are made from these records. There are two such amplifier-oscillograph systems, each permitting measurements from two body locations. The equipment has been previously described in greater detail by Davis (**2**, **3**). Maximum sensitivity in use during the present research was .40 microvolts input per millimeter of oscillograph screen deflection, while the least sensitivity was 2.63 microvolts.

Eighteen university students whose mean age was 19.22 ± .38 were used as subjects. The task required of them was to learn a blind stylus maze in which the only cues were kinesthetic. The instrument used was Kellogg's adaptation of the Warden U-maze, described elsewhere by Kellogg (**6**). Ten trials were given and subjects were instructed to 'learn the correct pathway as quickly and accurately as possible.' Time was measured by a stop watch and errors in terms of distance traversed were recorded

for each trial on a paper beneath the maze. Activity in terms of action potential levels was sampled from the dorsal surface of the forearms and the lower legs, at the area of greatest enlargement, during each of the ten trials and during each rest period between trials. The rest samples were taken ½ minute after work was finished; the work samples were taken 10 seconds or more after work commenced. Records were also made during rest before the learning began; that is, before the subject had been instructed in the task, and this record was used as a base in the computations. As a result there were 21 samples for each of the four limbs for each of the 18 subjects. Since there were 2 one-tenth of a second periods studied from each film record sample, and from each period 3 oscillograph deflections were measured, more than 9,000 measures are concerned in the results. After careful calibration of the sensitivity of the two systems, records were computed in terms of mean microvolts per oscillograph deflection, and figured in terms of rest levels. This procedure eliminates differences in the placement of electrodes from one to another and in the same electrode from subject to subject.

The Results

The average learning curves for the group are shown in Fig. 1. Time and error curves show typical trends, decreas-

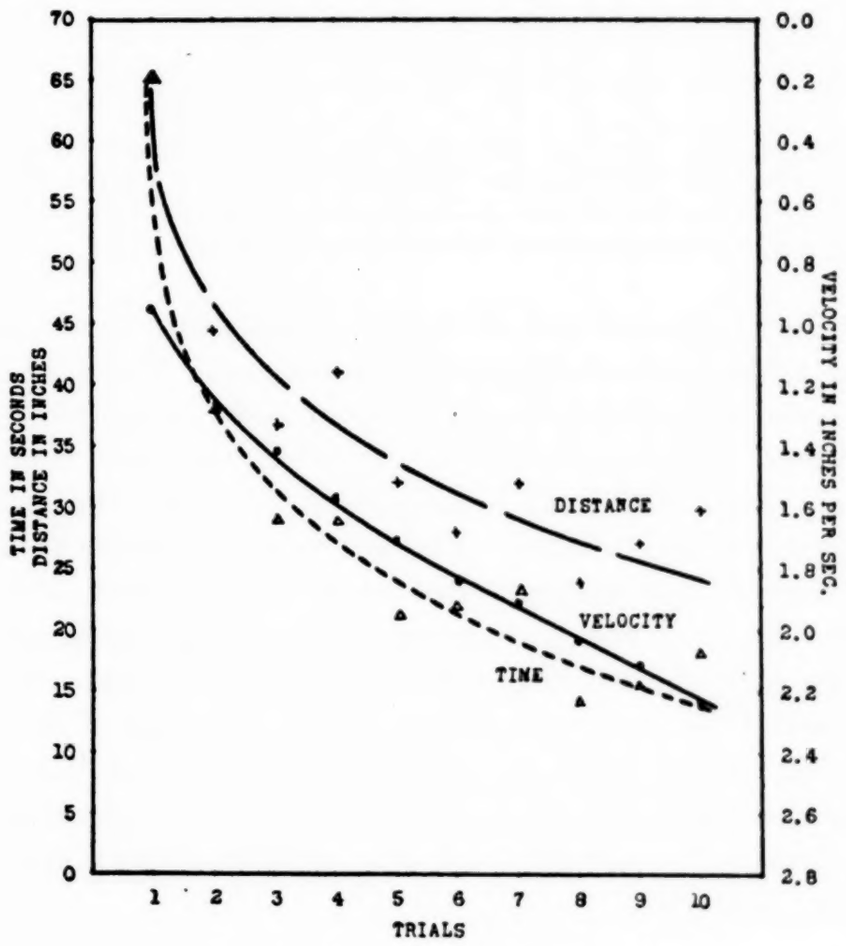

Fig. 1. Smoothed learning curves.

ing sharply in early trials and leveling off towards the end of the practice. Velocity is in terms of the number of inches covered in the maze pathway per second. Since both time and errors are involved in the velocity score, we may say that it is the best single indication of the acquisition of efficiency. Velocity scores are plotted in reverse order merely to facilitate comparison. Smoothing is by inspection. These typical curves may be accepted as evidence of the learning situation. Table 1 indicates the means for trials from the data on learn-

TABLE I

MEAN LEARNING SCORES

Measures	Trials										
	1	2	3	4	5	6	7	8	9	10	M
Velocity (inches per sec.)	.95 .31	1.29 .48	1.41 .41	1.56 .47	1.70 .55	1.83 .60	1.91 .82	2.03 .90	2.10 .90	2.23 .95	1.70 .57
Time (in seconds)	65.1 31	38.6 27	29.6 25	29.5 28	21.8 22	22.6 19	23.1 28	14.5 7	15.9 12	18.2 21	27.9 13
Accuracy (inches drawn)	65.1 34.0	44.1 23.3	36.8 23.2	41.3 34.6	32.7 31.2	28.8 21.8	32.8 23.3	24.2 4.4	27.0 19.1	29.9 24.9	36.2 17.3

Upper figures are means, lower figures are standard deviations.

ing. In the case of each of the three measures, the scores are means of individual subject's performance. Table II shows the mean tensional levels for the four body locations studied.

When tensional levels are plotted, peculiar U-shaped curves result. Although variability is high, the opposed trends are unmistakable. Tension in all members decreases during early learning, reverses at about trial five, and rises again. Data of non-performing limbs were grouped for comparison with the working right arm, and three stations were established by averaging trials 1–3, 4–7, and 8–10. The resulting curves (Fig. 2), expressed in terms of percent of initial rest, indicate most clearly the reversal phenomenon. The curves for interpolated rest periods reflect the same tensional pattern.

TABLE II

MEAN LEVELS OF TENSION FOR ALL SUBJECTS

Figures are in terms of mean microvolts per oscillograph deflection

Measures			Trials										
			R*	1	2	3	4	5	6	7	8	9	10	M
Work	Right arm			91.1 32.5	80.4 31.2	77.2 19.5	83.0 19.5	83.0 26.0	80.3 36.4	82.4 23.4	77.7 22.1	89.1 29.9	83.5 24.7	82.1 23.4
	Left arm			20.0 19.5	14.8 9.1	13.3 9.1	17.3 13.0	13.7 7.8	17.4 18.2	18.5 11.7	17.9 14.3	20.1 11.7	18.8 13.0	17.2 7.8
	Right leg			26.9 15.5	25.6 19.5	24.8 14.3	25.7 19.5	27.0 15.5	27.0 20.8	22.6 10.5	22.8 10.5	24.4 13.0	21.4 14.3	24.8 10.4
	Left leg			31.3 18.2	28.3 14.3	32.6 18.2	29.3 18.2	30.4 14.3	27.9 16.9	28.6 15.5	30.4 16.9	33.5 19.5	30.9 11.7	30.2 13.0
Rest	Right arm		14.1 9.1	12.6 10.4	10.5 9.1	15.5 11.7	12.4 7.8	12.8 11.7	13.1 14.3	11.5 7.8	13.7 9.1	14.0 10.4	15.4 10.4	13.1 7.8
	Left arm		8.5 9.1	10.9 10.4	7.5 6.5	8.4 7.8	6.3 3.9	7.2 6.5	6.8 5.2	8.7 6.5	7.5 5.2	8.4 5.2	11.3 16.9	8.3 5.2
	Right leg		23.7 24.7	19.7 10.4	15.2 7.8	18.8 13.0	18.5 14.3	16.2 10.4	17.1 13.0	20.4 19.5	21.0 13.0	18.7 13.0	17.0 7.8	18.0 9.1
	Left leg		25.0 24.7	21.7 10.4	20.9 10.4	27.3 15.5	17.4 14.3	19.7 10.4	14.4 14.3	22.6 19.5	24.4 13.0	16.5 14.3	17.8 7.8	20.0 9.1
Means of trials. % of initial rest.	Work	Right arm	100	585.3			579.8				588.9			580
		Other limbs	100	125.8			124.4				127.8			126
	Rest	Right arm	100	90.8			88.0				101.8			93
		Other limbs	100	87.0			76.1				82.9			81

* Initial rest.

Upper figures are means, lower figures are standard deviations.

DISCUSSION

An effort was made to relate these opposing trends to specific activities on the part of the subjects. The first clue came from a laboratory observation that subjects appeared at first to concentrate upon learning the correct moves with no thought to developing speed. Thus any speed increases

would be a function of decreasing distance rather than faster movements. Not until they had fairly well mastered the task did they attempt to speed up movements. Unfortunately no introspective reports were asked of the subjects.

The point may be developed statistically by reference again to the learning curves. Velocity is derived from distance divided by time, and according to the data, both of

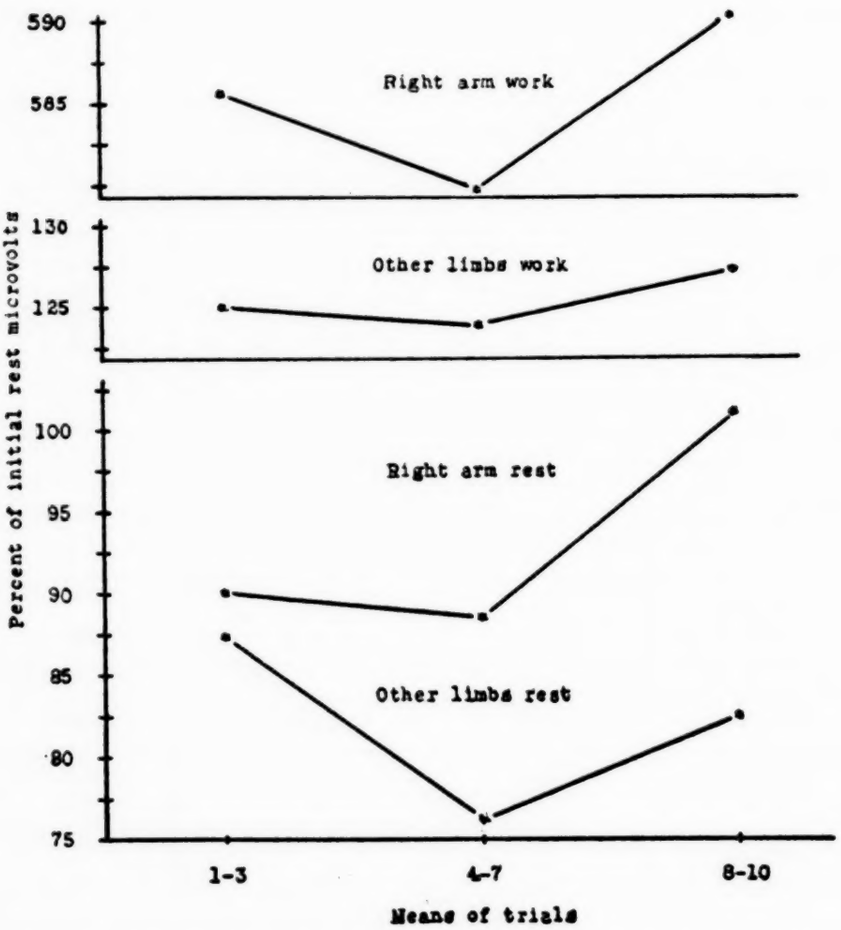

FIG. 2. Distribution of action potentials in four limbs in terms of percent of initial rest.

these are decreasing. If the rate of decrement of the two should remain constant and identical, then the velocity curve would be flat, a constant value; if they are unlike and constant, velocity is linear; if time decreases faster than distance, velocity is positively accelerated; and finally, if distance decreases faster than time, velocity is negatively accelerated.

The smoothed velocity curve shows evidence of such negative acceleration in the early trials and is almost perfectly linear in the later trials. This means, then, that for the 'average subject' distance is decreasing faster than time in the early trials. That is, subjects were improving accuracy faster than they were decreasing time. Likewise in the later trials, the linearity of the velocity curve indicates a constant rate of decrement in distance and in time. This means that speed and accuracy were later improving at more nearly a constant, unlike rate.

One point further. The modal trial where greatest accuracy for all subjects is first achieved is trial 5; the mean is trial 5.78. It is at this point that the subjects are likely to shift behavior from elimination of errors to increases of speed, especially since most of them made a perfect trial at this point in the learning to which the shift in behavior may be attributed. It is scarcely necessary to point out that this trial number roughly corresponds to the low point in the electromyogram curves.

As a tentative interpretation from these observations it appears reasonable to say that a decrease in activity is associated with the acquisition of accuracy, and an increase in activity with the acquisition of speed made possible by the accuracy attainment.

Turning away from the progressive changes for the moment, one finds another factor of interest. With one exception, the absolute mean levels of tension show the most active member to be the left leg, then the right leg, right arm, and left arm. The right arm is of course extremely active during work; otherwise the same relationship exists for the three periods studied—initial rest, work, and interpolated rest. The tensional level appears to be directly related to the distance from the preferred (working) limb. The same data, expressed in terms of percent of initial rest, may be seen in Fig. 3. This chart indicates that while the right arm is working, other limbs increase activity over rest in varying degrees, the left arm showing an enormous increase, and the left leg only slightly more than the right leg. Decreased interpolated

rests show an adaptation to the laboratory situation, while maintaining the same differential pattern. It would seem that postural factors and gradient patterns may eventually serve to explain these phenomena.

These results, although tentative, appear to fit well into the theoretical frame. The decreasing tension may be intimately associated with the development of a coördination

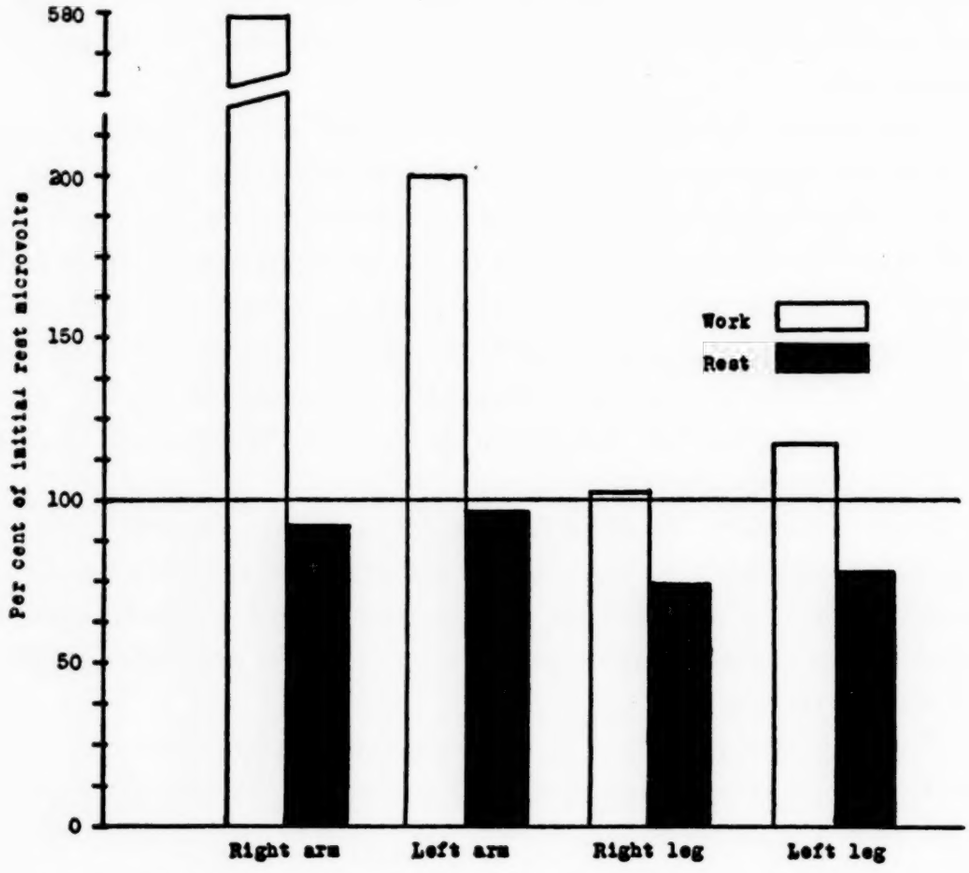

FIG. 3. Work and rest means of ten trials in terms of percent of initial rest.

pattern, and the increasing tension with increasingly efficient use of the coördination. These are two specific overt activities, yet the latter presupposes the former in precisely the same relationship as running to walking. As yet there is not a sufficient amount of data to attempt an answer to the question of variability of the pattern from subject to subject and from one point to the next in learning.

In conclusion one may again refer to the three earlier experiments on tensions during learning and reinterpret them in the light of these findings. Stroud's difficult mazes, where

performances gave decreases in tensions, undoubtedly were so classified because the subject made a large number of errors. On the other hand the 'easy mazes' were learned with few errors and increases in speed, thus giving increases in tensions. If he had put a difficult maze and an easy maze together into one, he would have had the same results obtained here. Ghisselli's findings corroborate the accuracy factor, since speed was not concerned. Bills' observation is in agreement with the relation of tensions to difficulty in performance, and Freeman noted the point concerning the differential tensional level for various muscle groups, which may be related to these findings also.

Summary

1. As learning progressed there was found a decrease in the tensional level followed by an increase lasting up to the point where practice was discontinued. Decreasing tension is associated with the elimination of errors and the development of a particular coördination. Increasing tension is associated with increased speed of performance and the more efficient use of the coördination.

2. Differential tensional patterns appear to persist in direct relation to the distance of the part measured from the performing member. The patterns found are suggested as being influenced by gradients and postural factors.

(Manuscript received December 17, 1938)

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STUDIES IN THE TRANSPOSITION OF LEARNING BY CHILDREN: II. RELATIVE VS. ABSOLUTE CHOICE WITH MULTI-DIMENSIONAL STIMULI

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This study is a sequel to one recently published in this journal by the author and three collaborators. The problem under consideration is the relation between the amount of practice on a discrimination habit and the type of response made upon transposition of the stimuli. In the earlier study, the results on the critical trials clearly indicated that, (1) the relative choice is made following a relatively small amount of post-fixation [1] practice, and (2) the absolute choice is made, in some subjects at least, after a relatively great amount of post-fixation practice. The question arises as to whether absolute choice would be made by all subjects if conditions were more favorable. It is the purpose of the present work to answer that question.

In addition to the factor of a great amount of post-fixation practice, another favorable condition for inducing absolute choice is a large difference between the stimuli employed. It is not intended to go to the extreme of Taylor (4) and Takei (3) and use stimuli of such radical difference (white, gray and black) that a stable relative choice probably would not be made even after very little practice. The aim is to select stimuli such that the relative choice would be made after a small amount of practice and the absolute choice would

[1] In these studies the term 'post-fixation' practice has been substituted for what has usually been referred to as 'over-learning.' All would agree that learning is not a process that ends as the learner reaches the norm, and consequently there could be no real 'over-learning.' We may define 'fixation' of a habit as that point beyond which it ceases to vary beyond certain arbitrary limits. The fixation point in these studies is placed at the beginning of a norm of 10 out of 10 perfect trials. A perfect trial is making the correct choice regardless of how much time may have been consumed in preparation for that choice.

be made after a great amount of practice. One way to insure the latter condition is to use stimuli between which there is a great difference, *e.g.*, with areas such that the ratio between them is $\frac{1}{4}$ or less. If such a small ratio between the stimuli is employed, the largest stimulus becomes inconveniently large and cumbersome. Another way to accomplish the same end is to use stimuli in which more than one characteristic are varied. The stimuli used in this work were varied in size (area), shape (degree of pointedness of a triangle), brightness (three grays), and pattern (distance between black vertical stripes). It may appear that a given stimulus which varies in so many ways from another would be perceived as a unique object. The criterion for continuity or non-uniqueness will be the appearance of a stable relative choice upon transposition at some early stage of learning. The results for the control group will show that these stimuli satisfy such a criterion.

Procedure.—The methodology followed was the same as described for the fourth experiment of the previous study except as noted below. Our subjects were eight children whose various characteristics are shown in Table I. They were obtained in the Bethany Day Nursery[2] of New York City. The work was carried on in the Day Nursery during the months of May and June of 1937.

TABLE I

SHOWING VARIOUS CHARACTERISTICS OF THE CHILDREN USED AS SUBJECTS

Name	Age in Months	IQ	Attitude in Experiment	Other Comments
Thomas.....	56	126	Excellent	Obviously enjoyed the work.
Eleanor.....	56	96	Excellent	Liked work quite well.
Marguerite....	56	—	Excellent	Satisfactory subject, but was very shy. Binet test could not be given.
Joyce.....	46	100	Excellent	Quite satisfactory. Was quiet and took work very calmly; liked work.
Ernest.....	57	102	Excellent	Always most anxious to work. Very interested.
Frank.....	56	100	Fair	Willingly came to experiment but always got impatient to get back to play.
Eddie.....	47	98	Poor	Was reluctant to give up play for the experiment. Responded impulsively in all trials.
Anton.....	53	125	Poor	Was reluctant to give up play for experiment each day. Was somewhat flippant and impulsive in reacting.

[2] We wish to express our appreciation to Miss Clash, Director of the Nursery School, for making the children available to us as subjects and for her kind coöperation in arranging a room for carrying on the work.

It was arranged to use the children in the mornings at such times as would not interfere with any of their regular activities. A room apart from the rest of the children in which there were no distractions was assigned for the experimentation. A detailed description of the apparatus employed was given in the account of the fourth experiment of the earlier paper.

The incentive conditions follow. If a child made a correct choice, he got a raisin which was delivered to him by means of the automatic reward box; if he made a wrong choice, a buzzer sounded. After a trial or two, the subjects did not choose to eat their raisins during the experiment. Some saved them till lunch and others took them home. A sort of social motive developed during the experiment. When the child returned to the playground, he would show his playmates how many raisins he had earned.

The stimuli were made of paper and pasteboard and attached to the stimulus-holders as previously described. The ratio between pairs of stimuli was as 5 is to 8. This ratio obtained for size, shape and pattern. The areas actually employed were 1250 sq.mm., 2000 sq.mm., and 3200 sq.mm. The middle triangle had a base and altitude of the same magnitude. The base of the smallest triangle was 5/8 of the base of the middle one and had the same altitude as the middle triangle. The base of the largest was 8/5 of the middle one and also had the same altitude as the middle one. In this arbitrary fashion the shape of the stimuli could be quantitatively graded. It is not suggested that the number of j.n.d.'s between the two pairs of stimuli were the same for either size or shape. However, this procedure was considered sufficiently good for the present purpose. The dimensions of the three stimuli were as follows: Altitudes for all three were 63.25 mm; bases were 39.63, 63.25, and 101.2 mm respectively. The pattern on the smallest stimulus took the form of black lines spaced 2.5 mm apart, on the middle one they were 4.0 mm apart, and on the largest they were 6.4 mm apart. The lines were approximately .8 mm in width. The brightness variable was not selected on a 5 to 8 basis. Instead three grays (Nos. 3, 15 and 28) chosen from the 0–30 series sold by Stoelting were used. The gray papers were so easily soiled by finger prints that it was necessary to arrange it so that the children did not touch them directly. Instead they used a light stick with a soft kleenex cushion on the end to push back the stimuli.

The subjects were divided into two groups. The control group had three in it and the experimental group five. Before beginning the regular training, all subjects learned a preliminary discrimination-habit for orientation. The stimuli used were very different from those used in the training and consisted of a black pentagon with a white border and a black octagon with a white center. This discrimination habit was learned very quickly by most of the subjects. All subjects were then trained on the smallest and the middle-sized, four-variable stimuli. The larger of the pair was positive and subsequent transposition was upward. Training continued at the rate of twenty-five trials per day until the norm of 10 perfect trials in succession were made. After reaching the norm, the control group was given twenty-five post-fixation trials per day immediately followed by three transposition trials. This routine was carried on for eight more days. Following fixation of the habit the experimental group was given twenty-five trials daily but with no transposition trials until the eighth day on which five were given. Choice *time* was taken for each trial with a stop-watch.

Results.—The results are presented in Tables II and III. The former shows a summary of the responses made in the

TABLE II

SHOWING THE TYPE OF RESPONSE MADE ON CRITICAL TRIALS, AND ALSO THE NUMBER OF TRIALS REQUIRED IN THE PRELIMINARY AND IN THE TRAINING

Subject	Group	No. Trials of Practice				Type of Response in the Critical Trials				
		Preliminary Regular Training								
			To Norm	The Norm	Beyond Norm	1	2	3	4	5
Ernest.....	Con.	8	3	10	25	Rel.	Rel.	Rel.		
					50	Rel.	Rel.	Rel.		
					75	Abs.	Abs.	Abs.		
					100	Abs.	Abs.	Abs.		
					125	Abs.	Abs.	Abs.		
					150	Abs.	Abs.	Abs.		
					175	Abs.	Abs.	Abs.		
					200	Abs.	Abs.	Abs.		
Joyce.....	Con.	27	19	10	25	Rel.	Abs.	Abs.		
					50	Rel.	Rel.	Rel.		
					75	Rel.	Rel.	Rel.		
					100	Rel.	Rel.	Rel.		
					125	Rel.	Rel.	Rel.		
					150	Rel.	Rel.	Rel.		
					175	Rel.	Rel.	Rel.		
					200	Rel.	Rel.	Rel.		
Anton.....	Con.	9	7	10	25	Abs.	Rel.	Rel.		
					50	Rel.	Abs.	Rel.		
					75	Rel.	Abs.	Rel.		
					100	Rel.	Rel.	Rel.		
					125	Rel.	Rel.	Rel.		
					150	Rel.	Rel.	Rel.		
					175	Rel.	Rel.	Rel.		
					200	Rel.	Rel.	Rel.		
Thomas....	Exp.	13	0	10	200	Abs.	Abs.	Abs.	Abs.	Abs.
Eleanor....	Exp.	9	1	10	200	Abs.	Abs.	Abs.	Abs.	Abs.
Marguerite	Exp.	12	2	10	200	Abs.	Abs.	Abs.	Abs.	Abs.
Frank.....	Exp.	7	1	10	200	Rel.	Rel.	Rel.	Rel.	Rel.
Eddie.....	Exp.	47	40	10	200	*Rel.	*Abs.	*Abs.	*Abs.	*Rel.

* These five responses represent a position habit.

critical trials. Each of the three subjects in the control group made at least two sets of stable relative choice in their eight sets of transposition trials. Ernest made stable relative choice after 25 trials practice, Joyce after 50 trials, and Anton after 100 trials. It might appear that these results are not

TABLE III

Subject	Group	No. of Pract. Trials Beyond Norm	Reaction Time in Seconds							Reaction Time as a Percentage of Practice Ave.	
			Pract.	Critical Trials					Av. of 1, 2 and 3	Crit. Trial No. 1	Ave. of C.T. 1, 2 and 3
				1	2	3	4	4			
Thomas....	Exp.	200	2.1	5.0	3.0	2.5	2.0	2.0	3.5	268	167
Eleanor....	Exp.	200	2.5	16.0	13.0	4.0	2.0	3.0	11.0	640	440
Marguerite	Exp.	200	1.5	2.0	2.0	2.0	3.0	3.0	2.0	133	133
Frank.....	Exp.	200	1.7	3.0	3.0	3.0	2.0	2.0	3.0	176	176
Eddie.....	Exp.	200	1.3	3.0	2.0	2.0	2.0	2.0	2.3	231	177
Ernest.....	Con.	25	2.6	5.5	3.5	3.0			4.0	212	154
		50	3.6	5.0	2.0	3.0			3.3	139	92
		75	1.4	2.5	2.0	2.0			2.2	179	157
		100	1.4	3.0	3.0	2.0			2.7	214	193
		125	1.4	3.5	2.0	2.0			2.5	250	179
		150	1.4	2.5	2.5	3.0			2.7	179	193
		175	1.3	2.0	1.0	2.0			1.7	154	131
		200	1.6	3.0	2.0	2.0			2.3	187	144
Joyce.....	Con.	25	3.8	5.5	3.5	3.5			4.2	147	115
		50	3.8	4.5	4.5	3.5			4.2	120	115
		75	3.9	4.5	6.0	4.5			5.0	115	128
		100	2.2	2.5	3.0	3.0			2.8	114	127
		125	1.8	2.5	2.5	2.0			2.3	139	128
		150	2.2	4.0	3.5	3.0			3.5	182	159
		175	2.2	2.0	2.0	2.0			2.0	91	91
		200	2.1	3.0	2.0	2.0			2.3	143	110
Anton.....	Con.	25	2.5	4.5	2.0	2.0			2.8	180	112
		50	2.7	5.0	5.5	3.0			4.5	185	167
		75	3.1	4.0	2.5	3.0			3.2	129	103
		100	2.0	2.0	2.0	2.0			2.0	100	100
		125	1.7	2.0	2.0	2.0			2.0	118	118
		150	1.4	1.5	1.0	1.0			1.2	107	86
		175	1.3	2.0	2.0	2.0			2.0	154	153
		200	1.6	2.0	1.0	2.0			1.7	125	106

consistent or lawful since 'stable relative' choice did not begin after the same amount of practice for the different subjects. To account for this wide variation, attention is called to the following facts. First of all, it has been previously shown (1) that amount of practice is an important factor in determining whether response will be 'unstable' or 'stable relative.' Also it is a well established fact that practice is effective in pro-

portion to the degree of motivation. Finally, wide differences in motivation among the three subjects were independently observed by two experimenters (see Table I). It is highly probable that 100 trials of practice with Anton's degree of interest may yield about the same learning effect as 50 trials with Joyce's degree of interest, or as 25 trials with Ernest's degree of interest. The transposition results for the control group are exactly what would be expected if that were true. The correlation between the observed degree of motivation and the number of practice trials required to reach a stable relative choice is a perfect negative. These results, though based on but three cases, seem to be strictly lawful. The absolute choices made by Ernest following his stable relative choices will be discussed at a later point.

No critical trials were given the experimental group until after 200 post-fixation practice trials. At that stage of practice, three of the five subjects made 'stable absolute' choice through five critical trials. It is significant to observe in this connection that these three subjects were more interested in the experimental task than the two who failed to make 'stable absolute' choice (see Table I). Eddie, the least well motivated of the group, required a far greater number of trials to learn both the preliminary and the regular discrimination habit than did the others. It appears that even 200 trials of practice, combined with the low motivation of this subject, produced little learning effect. Consequently, the habit disintegrated upon transposition of the stimuli. The subject regressed to the position habit that had been troublesome in his first attempts to learn the discrimination. In the critical trials he did not study the stimuli, or manifest so-called comparison-behavior. Instead, he immediately chose the stimulus on the left. Subject Frank learned both discrimination habits quickly. His sub-average motivation appeared in another form. Each day, before the training was complete, he became impatient to leave the experimental situation in order to get back to play. It seems reasonable that such a conflict of motives operates to decrease the effectiveness of the practice. Frank's results are just what would

be expected of a subject with reduced motivation. His stable relative choice then is in line with the finding of a previous experiment. In the latter it was found that while considerable practice yielded stable absolute choice, a moderate amount of practice yielded stable relative choice. Accordingly, two hundred trials practice with 'normal' motivation may produce stable absolute choice, while the same number of trials practice with somewhat less than normal motivation may produce stable relative choice. If the motivation is considerably reduced, the same amount of practice may produce unstable response in the critical trials.

For the three subjects in the experimental group that made stable absolute choice, it cannot be determined at what stage of practice they changed from potential relative to potential absolute response. All that is known is that it took place under two hundred trials. The transition may be considerably under two hundred trials for well motivated subjects. The procedure for the control group does not favor absolute choice, still the results for Ernest show that the absolute response may occur after as little as fifty trials of practice. Judging by the transposition trials, the same stage of learning for Frank was somewhere beyond 200 trials. For Eddie it would be considerably beyond 200 trials of practice.

There are, obviously, tremendous individual differences in learning these tasks. It is also clear that there is not a close correlation between transfer effect and the number of trials of practice, even though there is good reason for expecting such a relationship. These results strongly suggest that 'number of trials practice' without any account for degree of motivation is not an accurate indication of the extent to which the task has been 'learned.'

The data for choice time is shown in Table III. For all subjects the choice time on critical trials, as compared with training trials, shows a marked increase. When comparison [3] is made between the training trials and the first critical trial the median percent increase, for the control and experimental

[3] In making these computations the results used for the control group were those for the last set of critical trials, *i.e.* 200 trials practice.

groups, is 43 and 131. When comparison is made between the training and the first three critical trials the corresponding values are 10 and 76. The increase in choice time was much greater for the experimental group than for the control group. This is just as would be expected since the procedure for the latter group allowed them opportunity to become somewhat habituated to the transposition stimuli. Through the eight sets of critical trials for the control group the percent increase remained about the same. Through a set of critical trials the percent increase characteristically decreased from trial to trial. For example, the first subject (Ernest) required 5.5, 3.5, and 3.0 seconds respectively for his first three critical trials. This indicated rather rapid readjustment to the transposed stimuli for the practice time averaged 2.6 seconds.

Finally, in order to justify the use of the four-dimensional stimuli selected for this experiment, attention is called again to the relative choices made by the control group. All these subjects given critical trials after only a little practice made stable relative choices. The fact of that type of response makes it clear that these stimuli were not so unique that they could not be perceived as a continuum.

Discussion.—The results of this study stand as a verification of those presented in the earlier paper. Potential transfer effects, in the transposition experiment, pass through three stages as training is increased. These are: unstable response, stable relative response, and stable absolute response. The last stage would undoubtedly appear in all subjects provided the proper conditions were obtained. Important among these conditions are the following: (1) The stimuli must be sufficiently disparate; (2) the subjects must be well-motivated; (3) the degree of post-fixation practice must be relatively great; and (4) probably critical trials should not be given until the end of the practice, that is, there must be little or no opportunity for practice with the transposed stimuli.

The psychological mechanisms involved in these transitions from one stage of transfer to another have been suggested in an earlier report. That interpretation is in terms of the

conditioned response. The results of this study conform very well to that formulation. Here, as in the previous experiments, the absolute response appeared to be a function of restricted generalization of the positive stimulus and perhaps both stimuli. Such differentiation presumably was induced by the relatively great amount of practice of the original habit.

No attempt will be made here to fit generalization curves to the data, as was done in the earlier report. The construction of such curves could best be done on the basis of a larger number of subjects that are quite homogeneous with respect to age, learning ability for this kind of material, and most of all motivation toward this particular type of experiment. The latter implies taking into consideration not merely the child's like or dislike of the experiment as such, but also the relative position of the experiment in his repertoire. In other words what are the alternative attractions at the time of experimentation? Only after these factors are under good control may we hope to predict what choice a given child will make on a given set of stimuli after a given amount of practice. We believe that the present experiment approaches such conditions close enough to see that the phenomenon under consideration is strictly lawful. Perhaps some of the most important factors have been suggested.

With regard to the results on choice time, little needs to be added to the statement that they verify similar results reported earlier. They show clearly that upon transposition of the stimuli the subjects are frustrated. Obviously, a readjustment takes place before any overt response is made. If the subject's behavior is any index of the perceptual processes going on, he does not perceive the transposed stimuli as equivalent to the training stimuli. The modification of behavior in the critical trials has not been countenanced by Klüver who is responsible for the concept of 'equivalence.' This concept seems to imply that there is a definite line of demarcation between the equivalent and the non-equivalent stimuli. The present experimental work shows that such is far from the case. Although analysis of transfer in terms

of equivalent stimuli is in advance of analysis in terms of identical elements, both interpretations imply that transfer is static. We believe that analysis in terms of generalization is more comprehensive and more accurate, and that it brings into play many more of the dynamic factors which are involved in transfer.

Summary.—Eight pre-kindergarten children were trained to choose the larger, darker, wider, and less striped of two four-dimensional stimuli. They were then given two hundred trials of practice at the rate of twenty-five trials per day. Three of the eight received three critical trials on transposed stimuli, following each day's practice. The other five were given no transposition trials until after the two hundred trials of practice. Of the latter group three subjects made stable absolute choice through five transposition trials. All three of the former group made stable relative choice in at least two sets of critical trials.

Choice time was markedly greater for the transposition trials than for the training trials. The percent of increase in choice time was greater for the five subjects in the experimental group than for the three in the control group.

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DIFFERENTIAL TRANSFER OF TRAINING IN A ROTARY ACTIVITY

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Cross-education, by which is usually meant the transfer of training from one side of the body to the other, has been explained by the majority of its investigators as due to one or the other of two causal factors: to the generalization of methods (the transfer of common elements) or to the subminimal and simultaneous practice of the apparently untrained side.

The recent studies have employed a procedure which separately tested each hand and foot, then gave one of these members a large amount of training, and concluded with a final test of each of the trained and untrained limbs. Control groups were used to correct for the effect of the first test upon the second. The results of these experiments are not entirely conclusive. Certain investigators, especially, Bray (**1**) and Cook (**2**), have found that a transfer of training is effected from hand to foot as well as from hand to hand. Cook's finding that the transfer was greatest to the contralateral homologous limb and least to the contralateral heterologous limb seems to indicate that both the transfer of common elements and subminimal practice of the apparently untrained limb are present in cross education. In general, most of the recent investigators have tended to attribute most of the cross-education to the first factor, the generalization of methods resulting from the use of common elements.

Unfortunately, most of these recent studies have employed mirror tracing or mirror mazes, methods which of course

weight the results in favor of the common elements since perceptual factors are of much greater importance to mirror drawing than are speed, strength, or accuracy. The earlier experimenters on the other hand tended to confine their experimentation to activities weighted heavily in favor of the latter. These investigators, notably Davis (**3**) and his associates, attributed their results to subminimal practice. Although their experimental techniques are subject to some criticism, it seems to the present authors that when knowledge concerning cross-education is desired, the perceptual factors should be minimized and the motor skills should be stressed.

Moreover, the two explanations above mentioned do not exclude a third possibility. Cross-education might also be referred to the formation of mirrored incito-grams, *i.e.*, to the formation, in the non-dominant hemisphere of the cortex, of a mirrored representation of a learned pattern of muscular movements. Certain evidence exists in support of such an explanation. In the first mention of cross-education, Weber described it as accounting for the appearance of spontaneous mirrorscript when the left hand was used for writing. Since that time a great many instances of mirror-writing and mirror-functioning have been explained in such terms. Fuller (**4**) gives an excellent summary of this material. The utter inadequacy of the common-element theory in explaining these phenomena is very manifest. Other evidence also exists. Fieldes and Myers (**5**) in 1921 tested this type of cross-education. Subjects learned asymmetrical patterns as well as the letters by visual and non-visual methods. When learned while blindfolded, the correct form was chosen when traced over by the learning hand and the mirror pattern was chosen when traced over by the non-learning hand. Fieldes (**6**) in 1923 using fifty mentally retarded boys and girls found that forms learned during ten tracings and reproduced by both hands at once or first one hand and then the other showed that when a movement is learned first with one hand, there is a strong tendency to horizontal (left-right) reversal when tried with the opposite hand. Visual factors did not affect this. Hicks and Ralph (**7**) who also used subnormal

children found no transfer in the learning of a maze pattern with one hand. It is interesting to find such a result in view of Cook's finding that such transfer exists when college students are used as subjects. We would explain the differences as due to the fact that subnormal children developed a stereotyped sequence of muscular movements while the college students were able to develop a generalized and perhaps a visualized pattern. Thus the subnormals would perhaps have shown a high degree of transfer had the mirrored pattern been used. An important criticism of the cross-education studies using the mirror tracing of a star is that the direction of the movements around the star was not considered. In other words, if transfer to the symmetrical muscles is to be investigated the subject should trace around that star in a counter-clockwise direction if the training had been given in a clockwise direction. Since a sequence of muscular movements is what occurs in such experiments not only anatomical symmetry but functional symmetry should be our concern. Thus it was inexact of Cook to speak of transfer to the symmetrical and opposite muscles. Were the left hand to trace around the star in the same direction as the right hand no symmetrical functioning could be expected to occur.

In order to determine whether cross-education included not only the common elements but also some of the factors defined in the second and third hypotheses cited above, the following problem was formulated: If subjects were trained on a pattern involving rotary movement in a clockwise direction, would the greatest transfer to the untrained hand be in a counter-clockwise or in a clockwise direction? And, furthermore, would other subjects show just the opposite results when given training in a counter-clockwise direction? If clockwise training resulted in greater counter-clockwise transfer and vice-versa, then the differential results could not be explained in terms of the transfer of common elements, but must be attributed to other explanations.

Procedure.—The apparatus used in this investigation consisted of a pattern shaped like a clover leaf which was formed by three incomplete circles, 8 inches in diameter, cut out of a board and mounted on heavy supports. The track of the endless maze

thus formed was ¾ of an inch in width. A right-angled stylus was used, the long arm serving as the handle while the short arm, bearing a roller for ease in circling movements, held the stylus in the track and released a break key once every revolution. An electro-magnetically operated pen worked onto a Renshaw polygraph to record the number of revolutions. A bell was used as the signal to start and stop.

The procedure was divided into two one-hour periods, two days apart. The first period consisted of the following. Preliminary training and instructions were given in which speed of movement and consistency of hand grip while holding the stylus were stressed. For this preliminary training a second pattern was used. This pattern was formed by a single circle track 9 inches in diameter and 1 inch in width, cut from a board in a similar fashion to the pattern mentioned above. In this preliminary training the subject was given fifteen revolutions in both directions and with both hands in the same order as that used in the main experiment.

The first testing period on the clover leaf pattern then followed. This consisted of 8 trials of 28 seconds each with ample rest periods after each trial. The order of the test trials was LC, RCC, LCC, RC, RC, LCC, RCC, LC. R and L refer to right and left hands respectively, and C and CC to clockwise and counter-clockwise. This order was used to equate roughly the effects of previous trials. In this first period following the test the subject was given from five to eight 28-second training trials. One group of 10 subjects was trained RC, and another group of 12 subjects was trained RCC.

The second period was devoted to furthering the training until the subject had shown marked improvement. A gain of seven or more revolutions was considered adequate. The testing series was then repeated.

Results.—The statistical treatment given the data consisted of the computation of the average increments or gains (in number of rotations per time limit) made from test to retest by the right and left hands in both the trained and untrained directions. This permitted the combining of both groups of subjects thereby controlling experimentally any possible influence of preference in directional rotation. Each group's gains were separately analyzed as well, and since we were primarily interested in whether or not the left hand gained more when rotated in the direction opposite to that in which the right hand had been trained, standard errors and critical ratios for the differences between trained and untrained directions were computed for each hand and each group. These values are expressed in Table 1.

From this table it is apparent (1) that the training given the right hand in one direction improved the subject's ability to rotate the same hand in the opposite (untrained) direction. This result we would attribute to the training in efficient use of factors and skills common to both performances, such

factors, perhaps, as the perception of the spatial relationships between the three parts of the pattern. (2) It is clear, also, that the training given the right hand had a directional specificity. This is shown by the critical ratios between the performance of the right hand in the trained and untrained directions. The skill acquired by the subjects was not a greater general ability to rotate about the pattern with the right hand but a greater ability to rotate about the pattern with the right hand *in a certain direction.* (3) The results demonstrate a clear-cut transfer of training to the left hand in both directions. However, the significant finding is that this transfer was greatest in the direction opposite to that in

TABLE 1

AVERAGE AND DIFFERENTIAL GAINS FROM TEST TO RETEST IN NUMBER OF ROTATIONS

	Group Trained RCC		Group Trained RC		Combined Groups	
	R.H.	L.H.	R.H.	L.H.	R.H.	L.H.
Trained Direction (A)	11.7	4.8	14.1	4.3	12.7	4.6
Untrained Direction (B)	4.5	6.7	5.0	7.7	4.7	7.1
Average Difference (A–B)	7.2	−1.9	9.1	−3.4	8.0	−2.5
Standard Error Av. Diff.	1.63	.91	1.28	.73	1.03	.62
Critical Ratio	4.4	2.1	7.0	4.6	7.8	4.0
Chances in 100	100	98	100	100	100	100

which the right hand was trained. The critical ratios between the trained and untrained directions of the left handed performance show that this differential transfer in favor of the untrained direction is statistically significant. Such a result cannot be explained in terms of any theory of common elements. The cross-education produced by training the subjects in an RCC direction gave greater gains for LC rotation than for LCC. When, on the contrary, the subjects were trained in an RC direction, the left handed performance was greater in an LCC direction. When both groups of subjects were combined, the left hand showed a consistently greater ability to rotate in the direction opposite to that in

which the right hand had been trained. These results seem to indicate that the phenomena of cross-education are to be explained in terms of the second or third of the theories discussed in the introduction to this paper.

Moreover, it seems significant to us that the amount of transfer to the left hand in the trained direction is approximately equal to the improvement of the right hand in the untrained direction. No statistically significant differences were found between these two performances for either of the groups, thus indicating that the gains of the right hand in the untrained direction and the gains of the left hand in the trained direction are both to be explained in terms of the common element theory, *i.e.*, the subjects learned more about the pattern and technique of stylus rotation. No doubt part of the gain made by the left hand in the direction opposite to the training is to be explained in the same way, but not all of it. The difference between the gains made by the left hand in the trained direction and the greater gains made in the untrained direction must be due to other factors. These factors we believe to be either (1) the subminimal practice of the unused hand during right handed training, using the contra-lateral homologous muscles, or (2) the formation of mirrored integrations in the contralateral hemisphere of the cortex. Certainly some such explanation is more adequate than that to which cross-education is usually attributed.

Summary.—Using a continuous cloverleaf-patterned maze, one group of subjects was trained in clockwise and another group in counterclockwise rotation using a right angled stylus. Tests given prior and subsequent to training indicated (1) that training was specific to direction of rotation and (2) that the transfer of training to the left hand was greatest in the direction opposite to that used in training the right hand. The inadequacy of the theory of transfer of common elements to explain these results was discussed.

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DECREMENTAL AND INCREMENTAL EFFECTS OF DISTRACTING STIMULI UPON THE SALIVARY CRs OF 24 ADULT HUMAN SUBJECTS (INHIBITION AND DISINHIBITION?)

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The Problem

Experimenters in Pavlov's laboratory have repeatedly noted that distracting stimuli may cause either a decrement or an increment in the salivary CRs of dogs (**1**, **3**, **5**, **6**, **12**, **13**, **16**). Since the incremental effect occurred as a rule only when the conditioning was decremented as a result of delay, differentiation, or extinction, Pavlov named the phenomenon 'disinhibition,' assuming it to be due to a releasing of the CRs from some state of 'internal inhibition.' While a great deal may be said against the hypothesis of 'internal inhibition,' the study of the determining factors of decremental and incremental effects of distracting stimuli at this level of glandular behavior is in itself of considerable interest, and as such of course independent of any particular assumptions. It may be, perhaps, best investigated in the field of experimental extinction where the CRs could readily be made to range all the way from 100 percent efficacy to total ineffectiveness—from minimum to maximum internal inhibition, in Pavlov's conception. (Other ways of studying it would be to vary the intensities of the distracting stimuli, the similarities between the distracting and the conditioned stimuli, and the acquisition strengths of the conditioned stimuli.) The purpose of the present experiment was thus to study the effects of distracting stimuli upon the salivary CRs of 24 adult human subjects by introducing these stimuli at various stages of experimental extinction, and more specifically, by applying

them simultaneously with every even trial of a series of 24 non-reinforced applications of conditioned stimuli.

Procedure

The writer's general salivary CR technique with adult human subjects has been described before (**9, 10**) and will not be further detailed. It consists, first, of measuring salivation by increments in weights of dental cotton rolls (Johnson and Johnson, No. 3, 1.5 × 0.5 in) inserted under the subjects' tongues for a short period of time, usually one minute. To prevent evaporation, scale-corrosion and absorption, the rolls are weighed in small envelopes and reweighed immediately in the envolopes after the removal of the rolls from the subjects' mouths, and, again, since the cotton-in-the-mouth is by no means a totally inactive stimulus, periods of control salivation must be temporally rotated with experimental periods. Secondly, the technique involves presenting a series of stimuli during eating periods—tea-sandwiches, pretzels, lollipops, and chewing gum—of 2–4 minutes, and misinforming the subjects about the purpose of the experiment so as to forestall disturbing subjective sets and attitudes. Series of stimuli and comparatively long eating periods are used, as it was found that misinforming is unsuccessful and association sets can hardly be averted with the traditional single-conditioned-stimuli-plus-brief-reinforcements method. 'The effects of eye-fatigue upon digestion' is a serviceable misinforming technique with conditioned visual stimuli.

The 24 subjects of this study had previously salivary CRs to various patterns of miniature lights. These CRs were, however, also previously extinguished, and for the purpose of the present experiment all subjects were reconditioned to a red 15-w globular lamp, flashed intermittingly 40 times during 2-minute eating periods. The new CRs were quite regular and stable in all cases; their mean magnitudes ranged from from 176 ± 10.2 to 380 ± 14.5 mg. of net conditioned saliva (minus control saliva) in one-minute periods. The extinction and distraction trials were then begun. The conditioned 15-w light was flashed during 24 consecutive one-minute periods without reinforcement, and a small buzzer was sounded during the even-numbered periods of this series. Since distracting stimuli easily produce negative adaptation, each subject had only two distracting trials and each distracting trial was thus tested with only four subjects. Again, in order not to base the comparisons between the effects of different distracting trials only upon data from different subjects, each succeeding distracting trial had one common subject, and there were also common subjects in the distractions during extinction trials 2, 4; 8, 12; 14, 18; 20, 24; 4, 10; 16, 22; 2, 8; 6, 14; 16, 24; 10, 20; 12, 22; 4, 18; and 2, 24. The subjects were college undergraduates, between the ages of 18 and 22, and they were paid 50 cents an hour for their work. The experiment was conducted in a dimly lighted, fairly sound-proof room, between 3 and 5 o'clock in the afternoon.

Results and Conclusions

All the results are presented in Table 1. (The differences between the results from the same and from different subjects were too small to warrant an extra table.) Each entry in the first three main columns of this Table represents a mean of

net conditioned salivation—minus control salivation—of four subjects in periods of one minute. In the first column these salivations are from initial, pre-extinction trials; in the second column they are from trials preceding the distraction trials; and in the third column they are the conditioned salivations during the distraction trials. The last three columns of the Table express the effects of extinction and distraction as

TABLE 1

DECREMENTAL AND INCREMENTAL EFFECTS OF A BUZZER UPON THE CONDITIONED SALIVARY RESPONSES OF 24 ADULT HUMAN SUBJECTS TO A 15-W RED LIGHT

Each entry is a mean of 4 subjects, and in the first 3 main columns represents net conditioned salivation (minus control salivation) in mg. during one-minute periods. The last 3 columns represent the data in one column as a percent of the data of another column: the second in terms of the first, the third in terms of the second, and the third in terms of the first. The introductory column shows the ordinal number of the extinction trial at which the distraction was applied.

Extinction Trial When Buzzer Applied	CRs in Initial Pre-extinction Trials	CRs in Pre-distracting Trials	CRs in Distraction Trials	Pre-distraction as Percent of Pre-extinction	Distraction as Percent of Pre-extinction	Distraction as Percent of Pre-distraction
2	234±40.2	204±45.6	109±31.4	87.2	46.6	53.5
4	265±41.5	188±36.3	125±26.8	70.9	47.2	66.5
6	220±30.4	160±24.3	134±22.4	72.7	60.9	83.8
8	306±41.3	190±32.0	186±32.7	62.1	60.8	97.9
10	255±20.4	182±36.8	171±24.6	71.4	67.1	94.0
12	346±36.6	198±46.7	226±45.8	57.2	65.3	114.1
14	239±35.6	128±29.8	141±32.9	53.6	59.0	110.1
16	248±45.3	120±25.6	148±22.4	48.4	60.5	123.3
18	305±40.8	118±20.4	192±43.5	38.7	63.0	162.6
20	206±30.7	96±18.4	184±23.4	46.6	89.3	191.7
22	228±24.7	84±14.6	182±28.2	36.8	79.8	216.7
24	289±41.9	72±20.9	230±48.7	24.9	79.9	319.4

Correlation (r) between degree of extinction and incremental effect of distraction = 0.91 ± 0.02.

percentages. Column 4 (column 2 divided by column 1) shows the degree of extinction in the predistraction trials, or the state of the CR just before the application of the distracting stimulus. Columns 5 and 6 (column 3 divided by column 1 and by column 2) give the effect of the distraction as a percent of the conditioning in the initial pre-extinction trials and in the diminished pre-distraction trials. The Table contains also the correlation (r) between degree of extinction

and incremental effect of the distracting stimulus. Probable errors are presented in all cases.

Examining the Table, a number of findings seem to stand out. First, it is of course obvious that the non-reinforced applications of the conditioned stimulus produced unmistakable extinction. The conditioned salivations in the pre-distraction—or extinction without distraction—trials was 87.2 percent of the original pre-extinction conditioning in the first extinction trial and only 24.9 percent in the last, and there were few reversals in the progressive slope of the extinction (columns 2 and 4). Second, it is just as definite that the distracting stimulus, the buzzer, had a marked effect upon the conditioning. It reduced the CR by nearly one half in one trial and tripled it in another, and in 6 of the 12 trials its effect was more than 30 percent in either direction (column 6). Third, it is quite evident that the incremental effect of the buzzer was a function of the degree of the extinction of the CR. The correlation between the two variables was 0.91 ± 0.02, and in only one case in the Table did the rank-orders of percent extinction and per cent distraction differ by more than two steps (columns 4 and 6). Fourth, it appears rather clearly that the incremental—or extinction-restoring—effect of the buzzer was greater than its decremental—or conditioning-suppressing—effect, since, with progressive extinction, the conditioning during the distraction trials increased not only in relation to the diminished pre-distraction conditioning but also in relation to the original undiminished pre-extinction CRs [1] (column 5). Finally, the data of the experiment fit a simple equation $D = 0.4a + 0.9b$ where D is the amount of conditioning during a distraction trial, a the amount of conditioning in a pre-distraction trial, and b the amount of extinction in a pre-distraction trial (the

[1] Let a be the amount of conditioning in a pre-distraction trial, b the amount of extinction in the trial, x and y respectively the decremental and the incremental effects of the distracting stimulus, D the amount of conditioning during a distraction trial; then in two succeeding distraction trials $D = ax + by$ and $(a - 1)x + (b + 1)y$. It is obvious that $(a - 1)x + (b + 1)y > ax - by$ only when $y > x$.

difference between the pre-distraction and the pre-extinction trials).

Summary

1. The effect of sounding a buzzer upon a salivary CR to a flash of a 15-w red light was studied in 24 adult human subjects. The buzzer was applied at 12 different stages of partial extinction of the CRs.

2. The buzzer was shown to exert a double effect: while it suppressed the existing conditioned salivation, it restored the loss of conditioned salivation resulting from extinction. The correlation between the degree of the extinction of the CR and the incremental effect of the buzzer was 0.91 ± 0.02.

3. The incremental, or extinction-restoring, effects of the buzzer were shown to be about 50 percent greater than the decremental, or conditioning-suppressing, influences. Specifically, the existing CRs were suppressed by about 60 percent and the extinctions were restored about 90 percent.

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